

**Final Technical Report for Award No. 06HQAG0150
July 1st, 2009.**

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Institution: Puget Sound Regional Council**

The Puget Sound Regional Council collaborated with various other agencies in Oregon State to acquire 1,549,015 acres of LiDAR data. This project was done for the Oregon LiDAR Consortium via a contract established by the Puget Sound LiDAR Consortium.

The data was collected over several years due to inclement weather that prevented the collection of data during the same leaf-off season. The data was flown and post-processed by the vendor, Watershed Sciences, according to the Puget Sound LiDAR Consortium technical specifications. The Puget Sound LiDAR consortium has done a series of Quality Assurance\Quality Check evaluations on the data and has concluded that the data meets the specifications.

For further details on the project and the resulting dataset see the Vendors project report below.

The data will be available to the public via the Oregon LiDAR Consortium.

LiDAR Remote Sensing Data Collection:

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Oregon Department of Forestry

Puget Sound LiDAR Consortium

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June 19, 2009

LIDAR REMOTE SENSING DATA COLLECTION: DOGAMI, ODF STUDY AREAS

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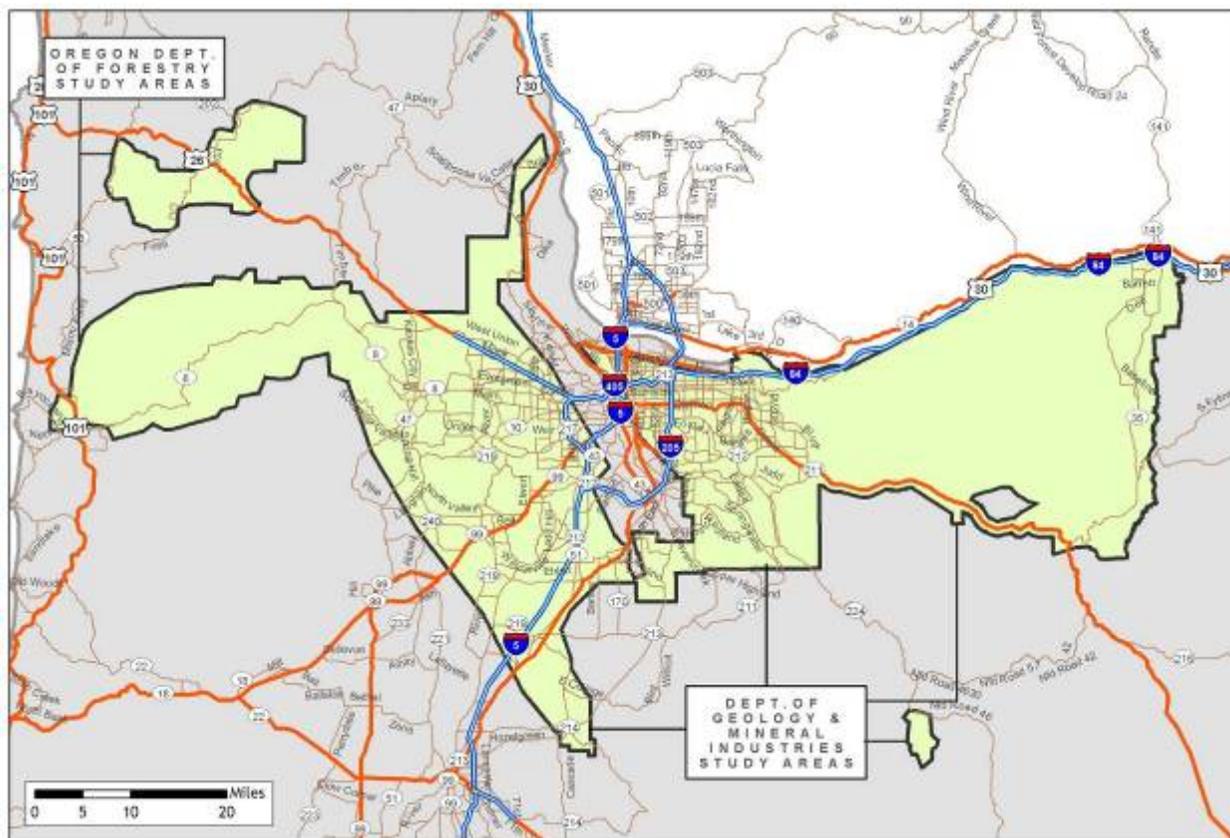
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1. Overview

1.1 DOGAMI and ODF Study Areas

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data for the Department of Geology and Mineral Industries (DOGAMI) and the Oregon Department of Forestry (ODF). The Areas of Interest (AOIs) cover portions of eight counties in northwest Oregon. The extent of requested LiDAR area totals ~1,549,015 acres; the map below shows the extent of the LiDAR area delivered, covering ~1,586,385 acres. The delivered acreage for the study area is greater than the original amount due to buffering of the original AOIs for flight planning optimization. This is the final, comprehensive data report for all areas in the LiDAR survey.

Figure 1.1. Extent of Department of Geology and Mineral Industries (DOGAMI) and Oregon Department of Forestry (ODF) Study Areas.



1.2 Areas Delivered

The total delivered acreage is detailed below.

ODF Area		
Delivery Date	AOI Acres	TAF Acres
September to December, 2007	305,930	314,950
Portland Area		
Delivery Date	AOI Acres	TAF Acres
October 15, 2007	207,046	210,945
November 1, 2007	115,136	118,909
November 12, 2007	164,418	167,193
January 29, 2008	80,397	83,576
February 19, 2008	115,092	116,652
March 4, 2008	23,829	23,829
April 4, 2008	74,035	77,753
April 11, 2008	73,856	74,582
December 4, 2008	29,565	32,659
January 23, 2009	41,859	42,288
February 13, 2009	65,318	65,429
February 27, 2009	34,345	35,035
March 11, 2009	22,019	22,424
April 10, 2009	15,035	15,715
April 17, 2009	23,163	23,937
May 7, 2009	47,087	48,325
May 27, 2009	110,883	112,184
<i>Total</i>	<i>1,549,015</i>	<i>1,586,385</i>

Figure 1.2. DOGAMI and ODF study areas, illustrating the delivered portion of the areas.

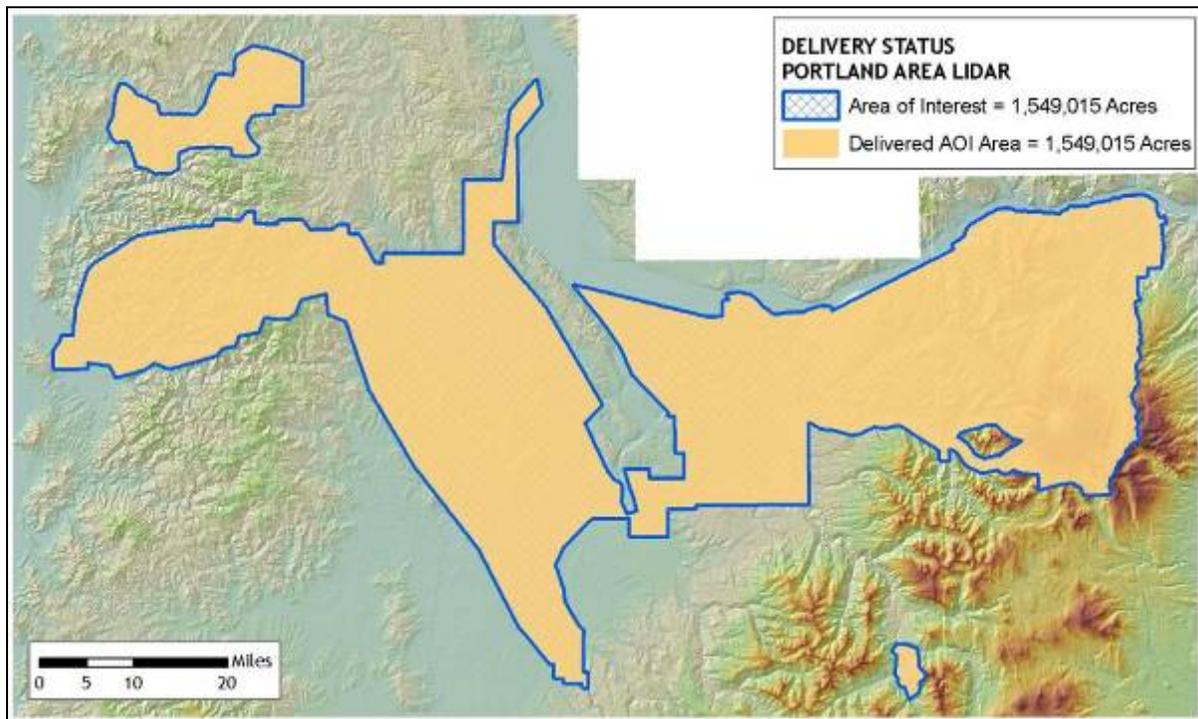
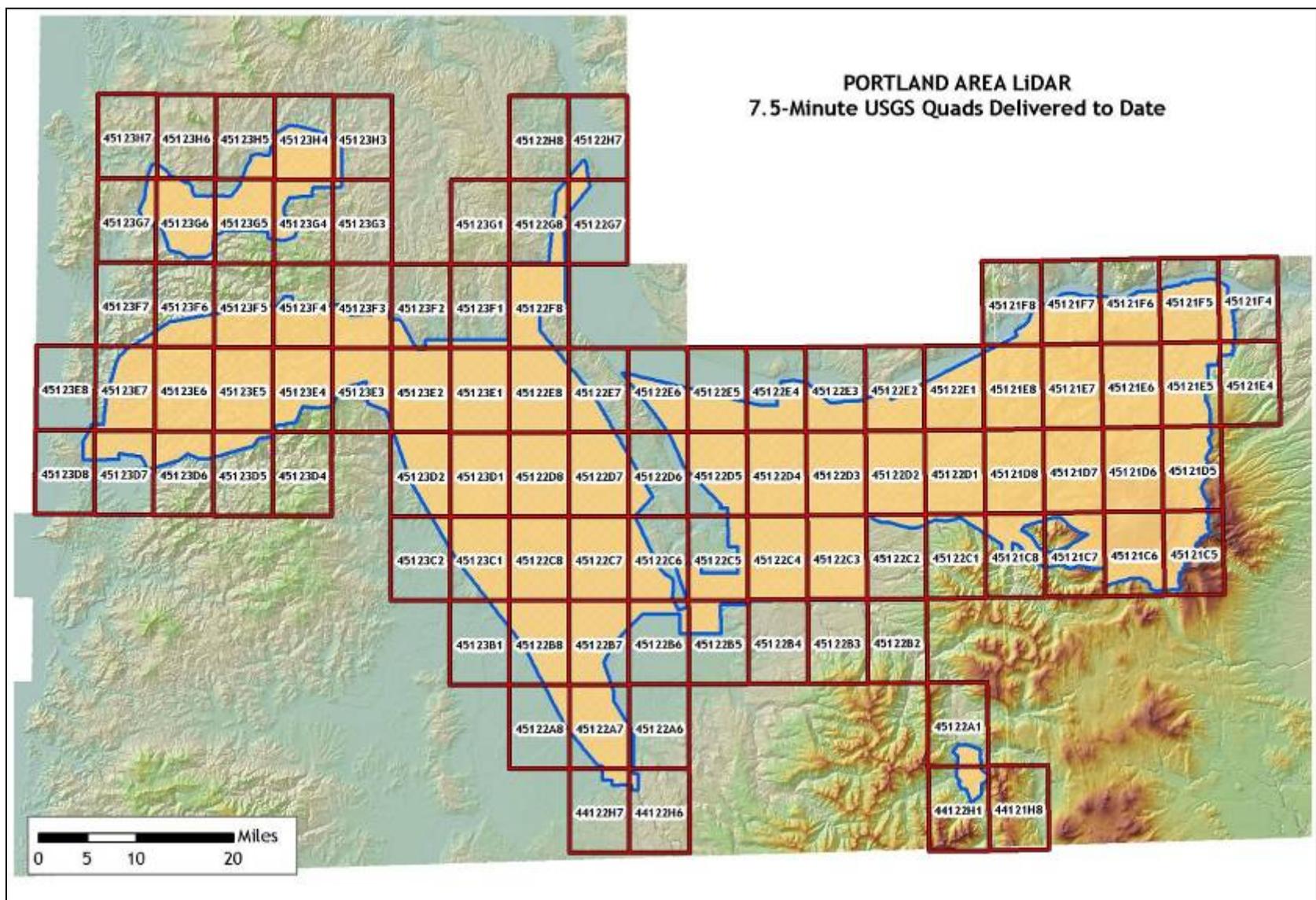


Figure 1.3. DOGAMI and ODF study areas, illustrating the delivered 7.5-minute USGS quads.



1.3 Accuracy and Resolution

Real-time kinematic (RTK) surveys were conducted in multiple locations throughout the study area for quality assurance purposes. The accuracy of the LiDAR data is described as standard deviations of divergence ($\sigma \sim \sigma$) from RTK ground survey points and root mean square error (RMSE) which considers bias (upward or downward). These statistics are calculated cumulatively for each acquisition year. For the DOGAMI / ODF study areas, the data have the following accuracy statistics:

	RMSE	1-sigma absolute deviation	2-sigma absolute deviation
2007 ODF and DoGAMI Data Acquisitions Processing Complete	0.11 feet	0.11 feet	0.23 feet
2008 DoGAMI Data Acquisition Processing Complete	0.13 feet	0.11 feet	0.27 feet

Data resolution specifications are for ≥ 8 pts per m^2 . Section 4.2 demonstrates that total pulse density for the Portland AOI delivered to date have the following statistics:

	Total Pulse Density	Ground Pulse Density
2007 ODF Data Acquisition Processing Complete	7.71 points per square meter 0.72 points per square foot	0.71 points per square meter 0.07 points per square foot
2007 DoGAMI Data Acquisition Processing Complete	6.90 points per square meter 0.64 points per square foot	1.28 points per square meter 0.12 points per square foot
2008 DoGAMI Data Acquisition Processing Complete	7.75 points per square meter 0.72 points per square foot	0.76 points per square meter 0.07 points per square foot

1.4 Data Format, Projection, and Units

Deliverables include point data in *.las v 1.1 and ascii format, 3-foot resolution bare ground model ESRI GRID, 3-foot resolution above ground surface ESRI GRID, 1.5-foot resolution intensity images in GeoTIFF format, Smoothed Best Estimate of Trajectory (5Hz frequency) information in ascii text format, and data report.

- ODF AOIs are delivered in Oregon Lambert, EPSG 2992, with horizontal units in International Feet and vertical units in US Survey Feet, in the NAD83/NAVD88 datum (Geoid 03).
- All other AOIs are delivered in Oregon State Plane North, with horizontal units in International Feet and vertical units in US Survey Feet, in the NAD83 HARN/NAVD88 datum (Geoid 03).

2. Acquisition

2.1 Airborne Survey - Instrumentation and Methods

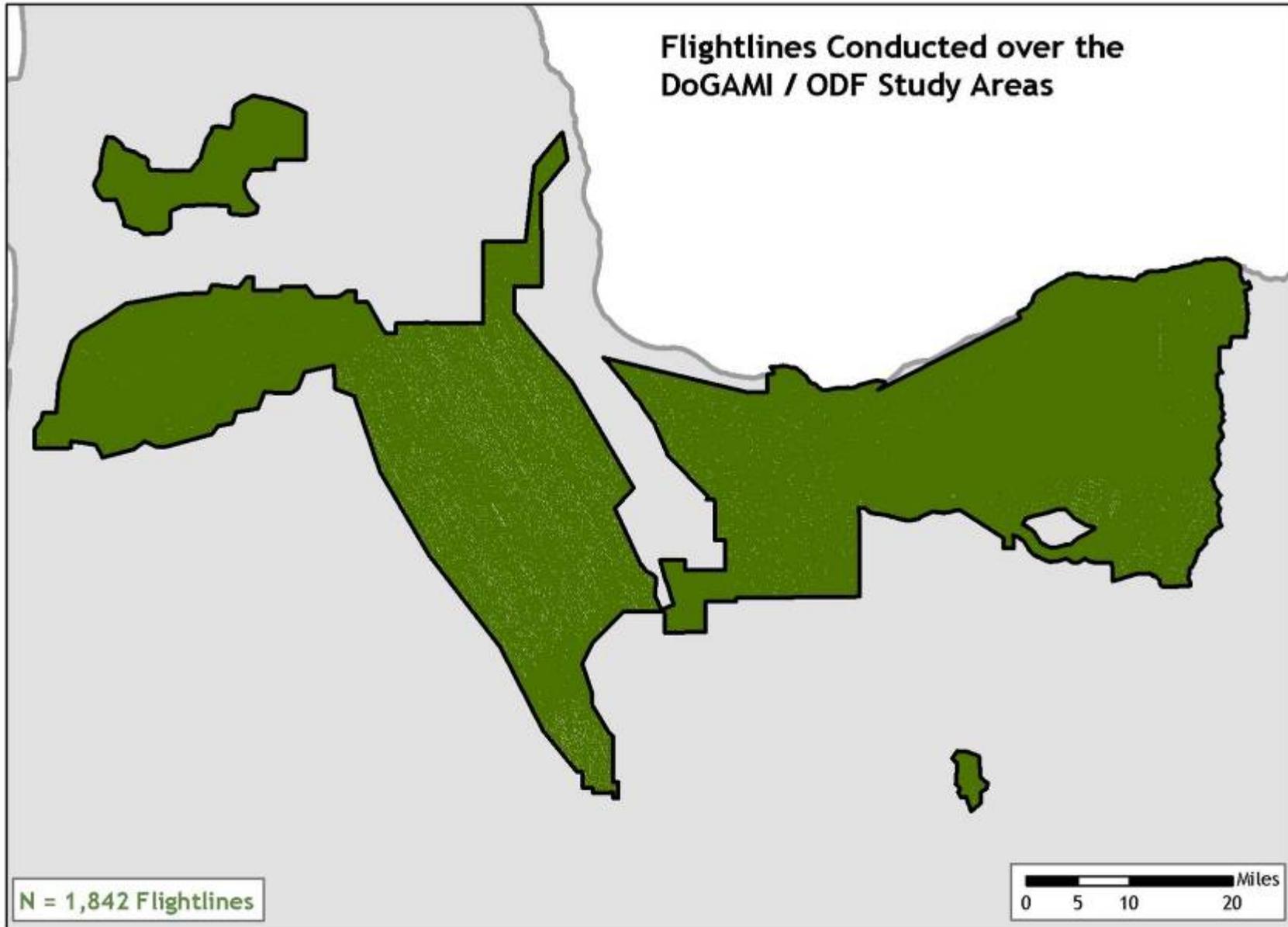
The LiDAR survey utilized a Leica ALS50 Phase II mounted in Cessna Caravan 208B and an Optech 3100 laser system mounted in a Cessna Caravan 208. The Leica ALS50 Phase II system was set to acquire $\geq 105,000$ laser pulses per second (i.e. 105 kHz pulse rate) and flown at 900 meters above ground level (AGL), capturing a scan angle of $\pm 14^\circ$ from nadir¹. The Optech 3100 system was set to acquire 71,000 laser pulses per second (i.e. 71 kHz pulse rate) and flown at 900 meters above ground level (AGL) capturing a scan angle of $\pm 14^\circ$ from nadir. These settings are developed to yield points with an average native density of ≥ 8 points per square meter over terrestrial surfaces. The native pulse density is the number of pulses emitted by the LiDAR system. Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and lightly variable according to distributions of terrain, land cover and water bodies.

The completed areas were surveyed with opposing flight line side-lap of $\geq 50\%$ ($\geq 100\%$ overlap) to reduce laser shadowing and increase surface laser painting. The system allows up to four range measurements per pulse, and all discernable laser returns were processed for the output dataset.

To solve for laser point position, it is vital to have an accurate description of aircraft position and attitude. Aircraft position is described as x, y and z and measured twice per second (2 Hz) by an onboard differential GPS unit. Aircraft attitude is measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU). **Figure 2.1** illustrates the location, swath width and overlap of the actual flight lines for the DOGAMI/ODF study areas.

¹ Nadir refers to the perpendicular vector to the ground directly below the aircraft. Nadir is commonly used to measure the angle from the vector and is referred to a “degrees from nadir”.

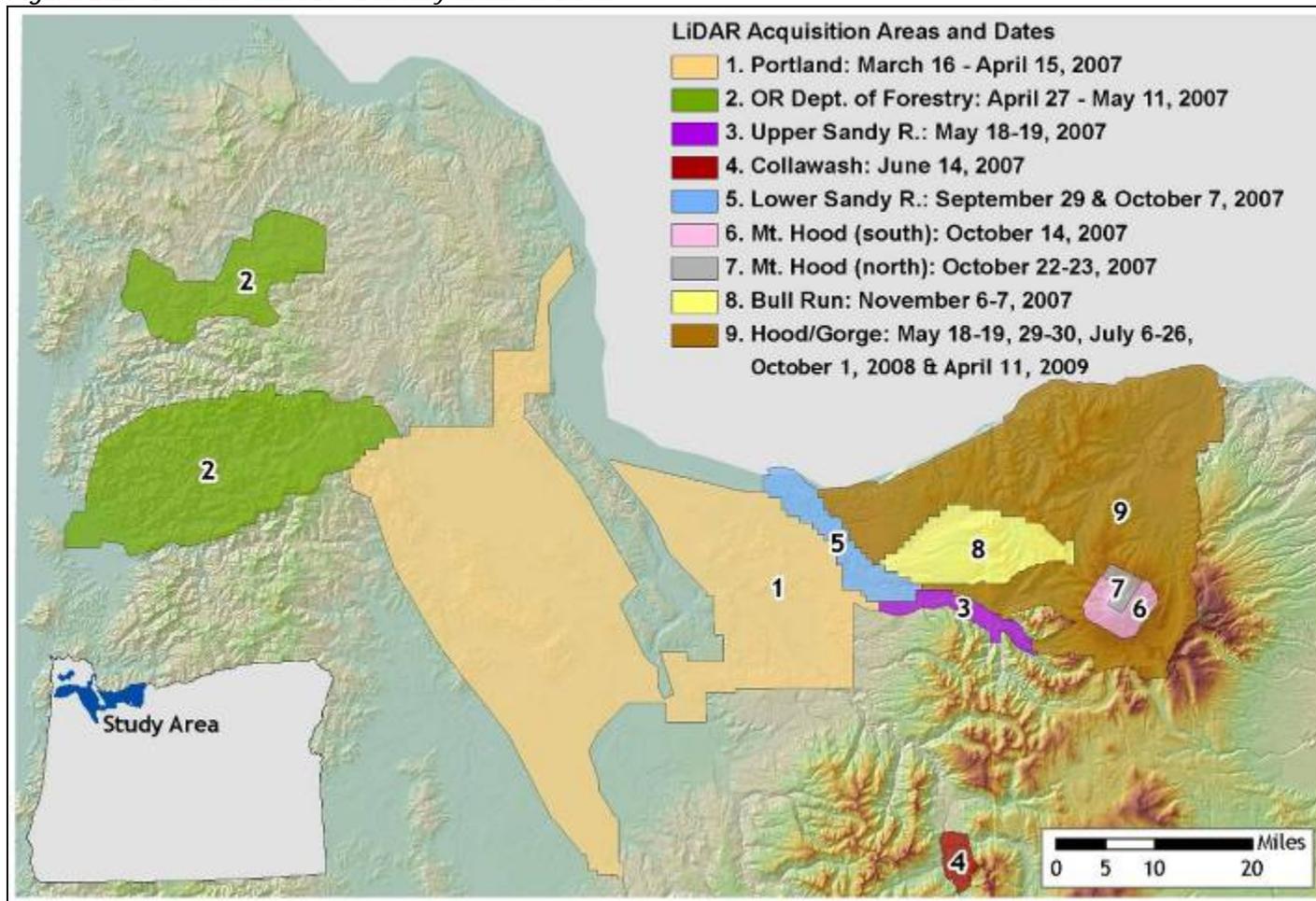
Figure 2.1. Actual flightlines in ODF and DOGAMI study areas.



2.1.1 Acquisition Specifics per Delivery Area

The DOGAMI and ODF study areas delivered to date are composed of nine unique study areas (Figure 2.2). Each area was flown during a unique time period and there is no overlap of LiDAR points between study areas. The LiDAR points that fall within each acquisition area represent the unique ground and vegetation conditions for the time period it was flown. Specifics for each area are discussed below.

Figure 2.2. DOGAMI and ODF Delivery Areas to Date.

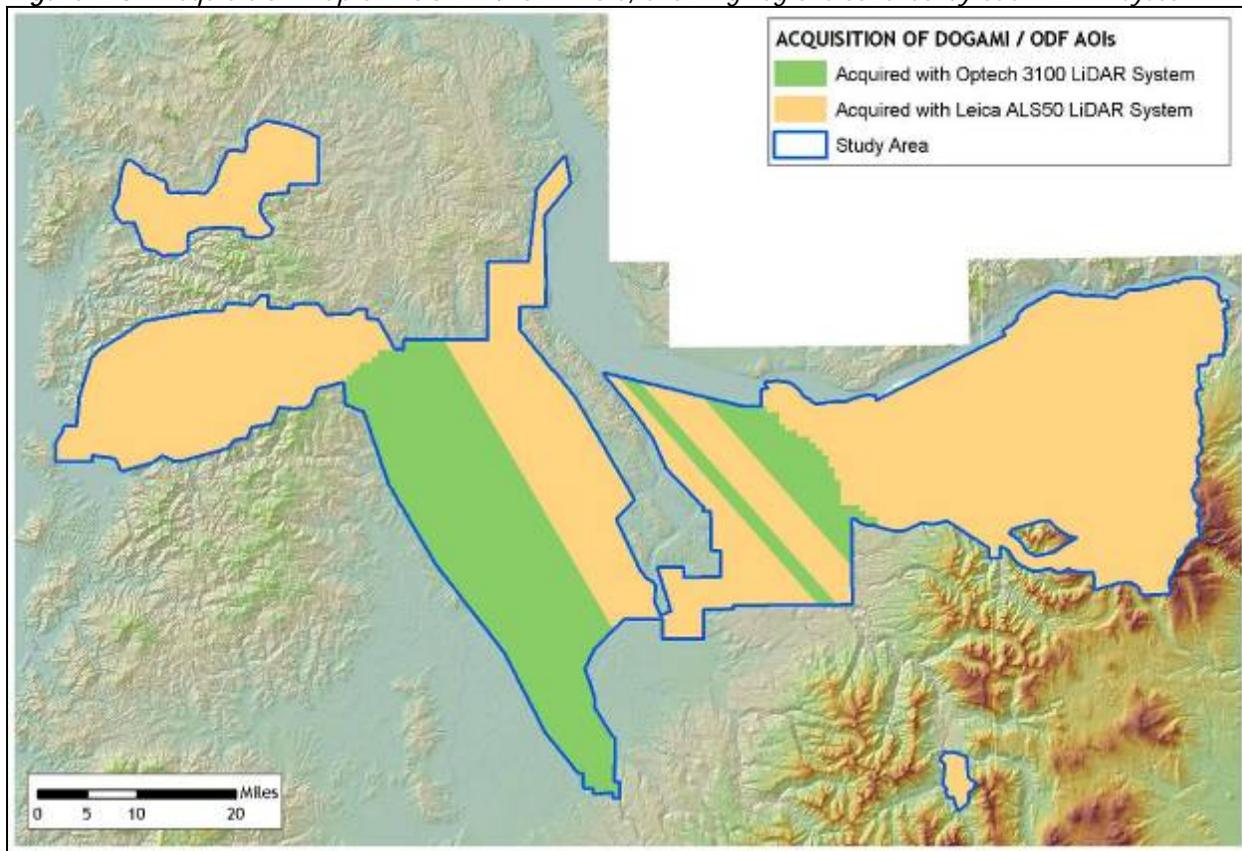


The data for the DOGAMI and ODF study areas were collected with two different LiDAR systems.

Table 2.1 LiDAR Survey Specifications

AOI	ODF, Upper Sandy, Collawash, Lower Sandy, Bull Run, portions of Portland, and Hood/Gorge.	Portions of Portland AOI	Mount Hood (Extreme Relief Areas)
Sensor	Leica ALS50 Phase II	Optech 3100	Leica ALS50 Phase II
Survey Altitude (AGL)	900 m	900 m	1800 m
Pulse Rate	>105 kHz	>71 kHz	>50 kHz
Pulse Mode	Single	Single	Single
Mirror Scan Rate	52 Hz	45 Hz	21 Hz
Field of View	28° (±14° from nadir)	28° (±14° from nadir)	28° (±14° from nadir)
Roll Compensated	Up to 15°	None	Up to 15°
Overlap	100% (50% Side-lap)	100% (50% Side-lap)	100% (50% Side-lap)

Figure 2.3. Acquisition map of DOGAMI / ODF AOIs, showing regions covered by each LiDAR system.



Delivery Area 1 - Portland: These data were collected between March 16 - April 15, 2007, with both the Leica ALS50 and the Optech 3100 LiDAR systems, as shown in Figure 2.4.

Delivery Area 2 - ODF: These data were collected between April 27 - May 11, 2007 with the Leica ALS50 LiDAR System.

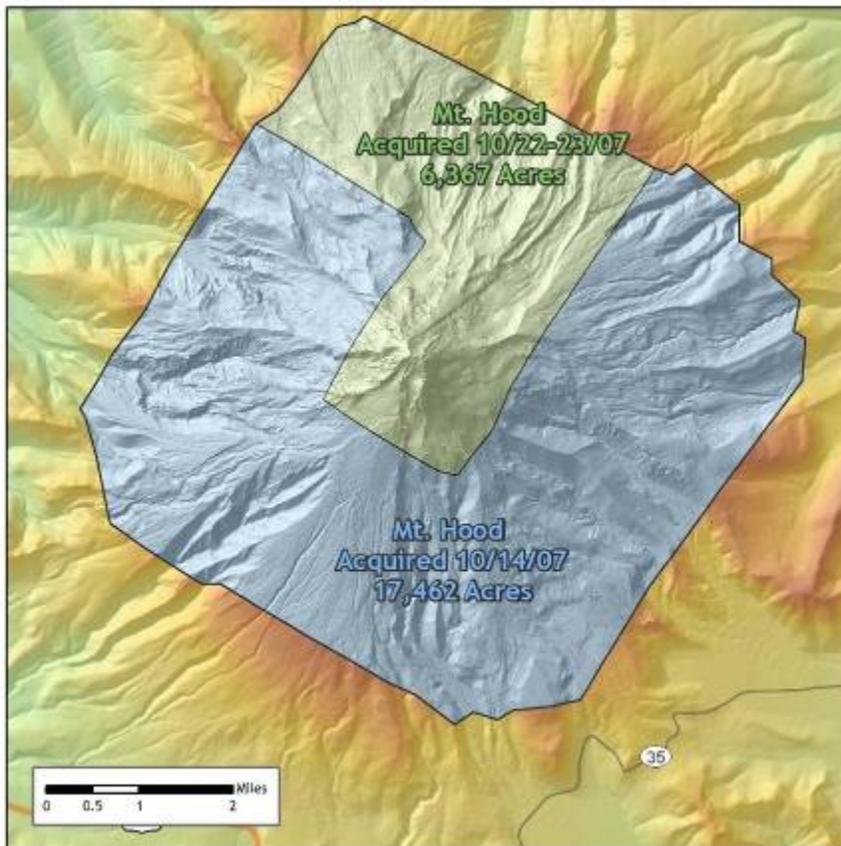
Delivery Area 3 - Upper Sandy River: These data were collected between May 18-19, 2007 with the Leica ALS50 LiDAR System.

Delivery Area 4 - Collawash: These data were collected on June 14, 2007 with the Leica ALS50 LiDAR System.

Delivery Area 5 - Lower Sandy River: These data were collected September 29 - October 7, 2007 with the Leica ALS50 LiDAR System.

Delivery Areas 6 & 7 - Mount Hood: These data were collected on October 14 and October 22-23, 2007 with the Leica ALS50 LiDAR System (in the Mount Hood high relief settings, see **Table 2.1**). Due to adverse weather, the area was acquired in two portions, one week apart. **Figure 2.4** below shows the extent of the Mount Hood area collected, visually divided into the two different acquisition windows. As a result, the two areas reflect two different snow levels, both accurate for the acquisition date in which they were acquired.

Figure 2.4. Mount Hood acquisition areas and dates.



Delivery Area 8 - Bull Run: These data were collected on November 6-7, 2007 with the Leica ALS50 LiDAR System.

Delivery Area 9 - Hood / Gorge: These data were collected on May 18-19, 29-30, July 6-26, October 1, 2008 & April 11, 2009 with the Leica ALS50 LiDAR System.

2.2 Ground Survey - Instrumentation and Methods

During the LiDAR survey of the study area, a static (1 Hz recording frequency) ground survey was conducted over monuments with known coordinates. Coordinates are provided in **Table 2.2** and shown in **Figure 2.5**. After the airborne survey, the static GPS data are processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS²) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and reported position accuracy.

Table 2.2. Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for the DOGAMI and ODF AOIs.

Study Area	Base Station ID	Datum NAD83(HARN)		GRS80
		Latitude (North)	Longitude (West)	Ellipsoid Height (m)
DOGAMI	ORMI_1	45 07 38.77347	122 47 50.69501	29.077
DOGAMI	SCJR_1	45 01 16.71080	122 44 37.15483	77.597
DOGAMI	ORMI_2	45 30 30.86516	123 05 27.70581	26.630
DOGAMI	ORMI_3	45 24 08.24317	122 54 59.88436	32.208
DOGAMI	ORMI_4	45 14 34.58806	122 46 02.63126	37.028
DOGAMI	SCJR3	44 54 08.93624	122 42 08.33058	325.829
DOGAMI	ORJR_1	45 19 53.37805	122 20 55.26176	95.011
DOGAMI	ORJR_2	45 27 24.86103	122 33 33.65264	181.756
DOGAMI	ORJM2	45 27 24.86103	122 33 33.65264	181.756
DOGAMI	ORJR5	45 46 22.21129	122 53 01.10672	3.562
DOGAMI	ORJR6	45 53 43.01413	122 48 48.08575	6.210
DOGAMI	ORSP14	45 52 23.25109	123 33 38.28134	108.139
DOGAMI	ORSP15	45 39 02.12095	123 16 33.08583	136.147
DOGAMI	ORSP16	45 39 02.12095	123 16 33.08583	136.147
DOGAMI	ORJR21	45 18 23.10077	121 49 49.67527	808.484
DOGAMI	ORSP20	45 23 19.99348	122 09 23.35649	359.167
DOGAMI	ORSP22	45 33 29.27716	122 38 34.17056	47.016
DOGAMI	RD4237	45 28 29.30798	122 23 46.92313	118.878
DOGAMI	MHJR1	45 19 52.00870	121 42 29.96298	1779.251
DOGAMI	MHJR2	45 19 52.09620	121 42 29.82020	1779.331
DOGAMI	MHJR3	45 19 49.38051	121 42 27.45942	1766.825
DOGAMI	BRCD1	45 26 38.51568	121 47 36.77702	844.046
DOGAMI	BRCD2	45 22 38.24522	121 13 33.71829	348.435
DOGAMI	ORSP28	45 07 30.53044	122 29 42.45664	248.593
DOGAMI	ORSP29	45 02 57.81336	121 58 55.33389	1261.986
DOGAMI	ORSP27	45 02 57.45546	121 58 55.35578	1261.736
DOGAMI	CDSD1	45 27 11.90589	122 17 20.60722	201.565
DOGAMI	CDSD2	45 33 3.80949	122 23 42.14002	-11.974

² Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

Table 2.2 (cont). Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for the DOGAMI and ODF AOIs.

Study Area	Base Station ID	Datum NAD83(HARN)		GRS80
		Latitude (North)	Longitude (West)	Ellipsoid Height (m)
DOGAMI	CDAP1	45 33 4.03516	122 23 41.80716	-12.027
DOGAMI	CDAP2	45 27 11.90589	122 17 20.60722	201.565
DOGAMI	HOODR01	45 34 7.17772	121 32 3.01136	615.155
DOGAMI	HOODR02	45 34 7.53745	121 32 2.45680	615.154
DOGAMI	HR3	45 50 19.31931	121 32 15.13764	169.179
DOGAMI	CLCF1	45 41 7.84953	121 51 18.81158	16.812
DOGAMI	CLCF2	45 41 0.16753	121 51 22.83026	17.309
DOGAMI	HCF1	45 36 9.25198	122 2 37.45339	0.146
DOGAMI	HCF2	45 32 43.93173	121 42 33.87275	422.973
DOGAMI	FLJ1	45 31 33.01482	122 8 20.68793	648.857
DOGAMI	FLJ2	45 31 7.77908	122 17 48.68460	197.157
DOGAMI	CLJ1	45 27 41.34656	121 46 36.49291	726.274
DOGAMI	CLJ2	45 27 41.38403	121 46 36.35757	726.334
DOGAMI	HLJ1	45 25 19.67182	121 49 5.41887	927.163
DOGAMI	HDCF1	45 23 49.10281	121 51 40.19938	756.402
DOGAMI	TMCF1	45 18 21.84889	121 42 8.43103	1431.959
DOGAMI	TMCF2	45 18 22.21004	121 42 7.46317	1433.992
DOGAMI	MHMC1	45 18 40.62153	121 38 40.56026	1408.434
DOGAMI	PWHAP2	45 33 3.93810	122 23 44.21777	-12.395
DOGAMI	PWHSD1	45 27 11.69280	122 17 20.83247	201.685
DOGAMI	RC1674	45 42 39.37193	121 32 59.76037	81.122
DOGAMI	GKHD1	45 41 56.21874	121 40 05.15627	10.851
ODF	ORSP10	45 51 45.02398	123 35 01.16219	139.9685
ODF	ORSP11	45 51 16.03468	123 32 26.33048	187.864
ODF	ORSP12	45 37 08.06456	123 23 50.39774	402.8955
ODF	ORSP13	45 29 59.43934	123 38 32.06929	280.969
ODF	ORSP14	45 52 23.25109	123 33 38.28134	108.139

Multiple DGPS units are used for the ground real-time kinematic (RTK) portion of the survey. To collect accurate ground surveyed points, a GPS base unit is set up over monuments to broadcast a kinematic correction to a roving GPS unit. The ground crew uses a roving unit to receive radio-relayed kinematic corrected positions from the base unit. This method is referred to as real-time kinematic (RTK) surveying and allows precise location measurement ($\sigma \leq 1.5 \text{ cm} \sim 0.6 \text{ in}$). For the DOGAMI and ODF study areas, 17,162 RTK points were collected. These were compared to LiDAR data for accuracy assessment. **Figure 2.5** shows base station locations and **Figures 2.5-2.29** show detailed views of RTK point locations. (Edit by PSLC: To reduce this report to 10 MB, Figures 2.6 to 2.29 have been omitted. To get a full report including these images please go to <http://pugetsoundlidar.ess.washington.edu/lidardata/flighttrajectory.html> and look for 2007-2008 Oregon LiDAR Consortium Project)

3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
Software: Waypoint GPS v.8.10, Trimble Geomatics Office v.1.62
2. Develop a smoothed best estimate of trajectory (SBET) file that blends the post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.
Software: IPAS v.1.4
3. Calculate laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Creates raw laser point cloud data for the entire survey in *.las (ASPRS v1.1) format.
Software: ALS Post Processing Software
4. Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).
Software: TerraScan v.9.001
5. Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are performed on ground classified points from paired flight lines. Every flight line is used for relative accuracy calibration.
Software: TerraMatch v.9.001
6. Position and attitude data are imported. Resulting data are classified as ground and non-ground points. Statistical absolute accuracy is assessed via direct comparisons of ground classified points to ground RTK survey data. Data are then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction. Ground models are created as a triangulated surface and exported as ArcInfo ASCII grids at a 3-foot pixel resolution.
Software: TerraScan v.9.001, ArcMap v9.3, TerraModeler v.9.001

3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets are referenced to 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collects 2 Hz kinematic GPS data. The onboard inertial measurement unit (IMU) collects 200 Hz aircraft attitude data. Waypoint GPS v.7.80 is used to process the kinematic corrections for the aircraft. The static and kinematic GPS data are then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. IPAS v.1.4 is used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session are incorporated into a final smoothed best estimated trajectory (SBET) file that contains accurate and continuous aircraft positions and attitudes.

3.3 Laser Point Processing

Laser point coordinates are computed using the IPAS and ALS Post Processor software suites based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) are assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data are output into large LAS v. 1.1 files; each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

These initial laser point files are too large to process. To facilitate laser point processing, bins (polygons) are created to divide the dataset into manageable sizes (< 500 MB). Flightlines and LiDAR data are then reviewed to ensure complete coverage of the study area and positional accuracy of the laser points.

Once the laser point data are imported into bins in TerraScan, a manual calibration is performed to assess the system offsets for pitch, roll, heading and mirror scale. Using a geometric relationship developed by Watershed Sciences, each of these offsets is resolved and corrected if necessary.

The LiDAR points are then filtered for noise, pits and birds by screening for absolute elevation limits, isolated points and height above ground. Each bin is then inspected for pits and birds manually; spurious points are removed. For a bin containing approximately 7.5-9.0 million points, an average of 50-100 points are typically found to be artificially low or high. These spurious non-terrestrial laser points must be removed from the dataset. Common sources of non-terrestrial returns are clouds, birds, vapor, and haze.

The internal calibration is refined using TerraMatch. Points from overlapping lines are tested for internal consistency and final adjustments are made for system misalignments (i.e., pitch, roll, heading offsets and mirror scale). Automated sensor attitude and scale corrections yield 3-5 cm improvements in the relative accuracy. Once the system misalignments are corrected, vertical GPS drift is then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy. At this point in the workflow, data have passed a robust calibration designed to reduce inconsistencies from multiple sources (i.e. sensor attitude offsets, mirror scale, GPS drift) using a procedure that is comprehensive (i.e. uses all of the overlapping survey data). Relative accuracy screening is complete.

The TerraScan software suite is designed specifically for classifying near-ground points (Soininen, 2004). The processing sequence begins by 'removing' all points that are not 'near' the earth based on geometric constraints used to evaluate multi-return points. The resulting bare earth (ground) model is visually inspected and additional ground point modeling is performed in site-specific areas (over a 50-meter radius) to improve ground detail. This is only done in areas with known ground modeling deficiencies, such as: bedrock outcrops, cliffs, deeply incised stream banks, and dense vegetation. In some cases, ground point classification includes known vegetation (i.e., understory, low/dense shrubs, etc.) and these points are manually reclassified as non-grounds. Ground surface rasters are developed from triangulated irregular networks (TINs) of ground points.

4. LiDAR Accuracy and Resolution

4.1 Laser Point Accuracy

Laser point absolute accuracy is largely a function of internal consistency (measured as relative accuracy) and laser noise:

- **Laser Noise:** For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise. The laser noise range for this mission is approximately 0.02 meters.
- **Relative Accuracy:** Internal consistency refers to the ability to place a laser point in the same location over multiple flight lines, GPS conditions, and aircraft attitudes.
- **Absolute Accuracy:** RTK GPS measurements taken in the study areas compared to LiDAR point data.

Statements of statistical accuracy apply to fixed terrestrial surfaces only, not to free-flowing or standing water surfaces, moving automobiles, et cetera.

Table 4.1. LiDAR accuracy is a combination of several sources of error. These sources of error are cumulative. Some error sources that are biased and act in a patterned displacement can be resolved in post processing.

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

4.1.1 Relative Accuracy

Relative accuracy refers to the internal consistency of the data set and 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). Internal consistency is affected by system attitude offsets (pitch, roll and heading), mirror flex (scale), and GPS/IMU drift.

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following was targeted at a flight altitude of 900 meters above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (i.e., $\sim 1/3000^{\text{th}}$ AGL flight altitude). Lower flight altitudes decrease laser noise on surfaces with even the slightest relief.
2. 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 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.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm 14^\circ$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. 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 19 km (11.5 miles) at all times.
5. Ground Survey: Ground survey point accuracy (i.e., < 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.
6. 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 most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.
7. Opposing Flight Lines: All overlapping flight lines are opposing. 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.

Relative Accuracy Calibration Methodology

1. 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 are calculated and applied to resolve misalignments. The raw divergence between lines is computed after the manual calibration is completed and reported for each study area.
2. Automated Attitude Calibration: All data are tested and calibrated using TerraMatch automated sampling routines. Ground points are classified for each individual flight line and used for line-to-line testing. System misalignment offsets (pitch, roll and heading) and mirror scale are solved for each individual mission. The application of attitude misalignment offsets (and mirror scale) occurs for each individual mission. The data from each mission are then blended when imported together to form the entire area of interest.
3. Automated Z Calibration: Ground points per line are utilized to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration is the final step employed for relative accuracy calibration.

Relative Accuracy Calibration Results

2007 Acquisition Areas

Relative accuracies have been determined for all portions of the DOGAMI & ODF study areas acquired in 2007 and delivered; the statistics are based on the comparison of 1,157 flightlines and over 12 billion points. For flightline coverage, see Figure 2.1 in Section 2.1.

- Project Average = 0.057 m
- Median Relative Accuracy = 0.079 m
- 1 σ Relative Accuracy = 0.106 m
- 2 σ Relative Accuracy = 0.173 m

Figure 4.1. Distribution of relative accuracies, non slope-adjusted.

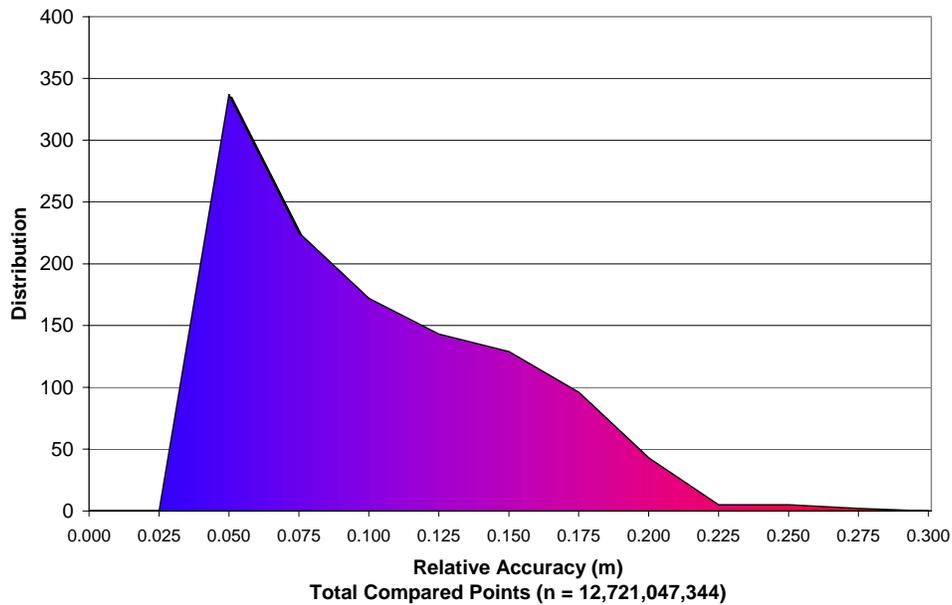
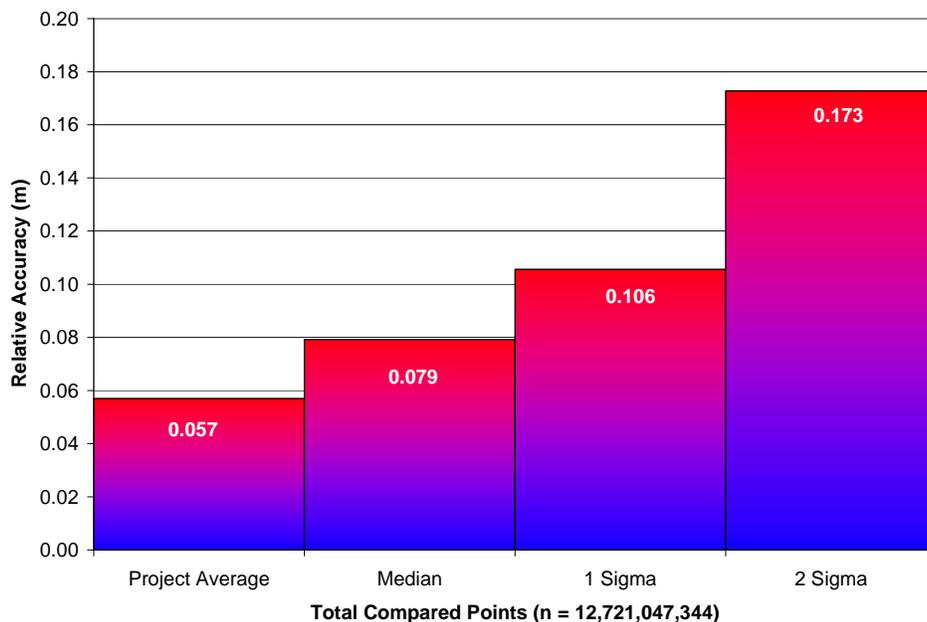


Figure 4.2. Statistical relative accuracies, non slope-adjusted.



2008 Acquisition Area

Relative accuracies have been determined for the entire DOGAMI study area acquired in 2008; the statistics are based on the comparison of 708 flightlines and over 3 billion points. For flightline coverage, see **Figure 2.1** in Section 2.1.

- Project Average = 0.067 m
- Median Relative Accuracy = 0.066 m
- 1 σ Relative Accuracy = 0.072 m
- 2 σ Relative Accuracy = 0.090 m

Figure 4.3. Distribution of relative accuracies, non slope-adjusted.

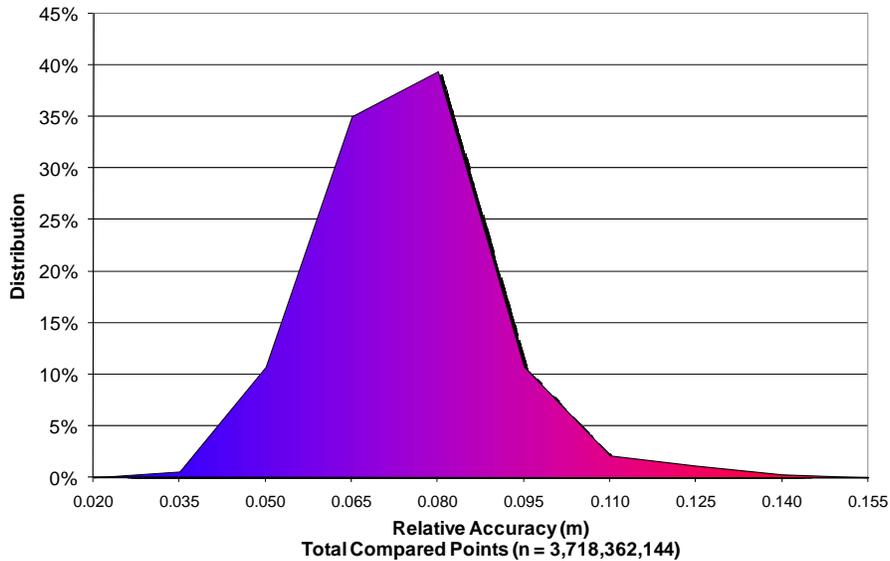
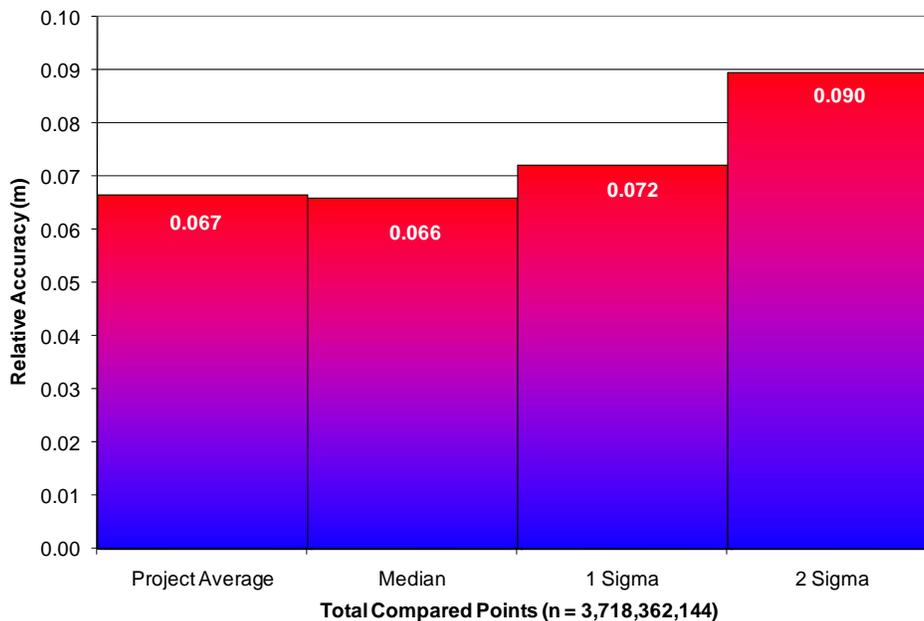


Figure 4.4. Statistical relative accuracies, non slope-adjusted.



4.1.2 Absolute Accuracy

2007 Acquisition Area

The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. For the DOGAMI and ODF study areas acquired in 2007 and delivered, 11,969 RTK points were collected. Accuracy statistics are reported in Table 4.2 and shown in Figures 4.5-4.6.

Table 4.2. Absolute Accuracy - Deviation between laser points and RTK survey points.

Sample Size (n): 11,969	
Root Mean Square Error (RMSE): 0.11feet	
Standard Deviations	Deviations
1 sigma (σ): 0.11 feet	Minimum Δz : -0.52 feet
2 sigma (σ): 0.23 feet	Maximum Δz : 0.45 feet
	Average Δz : 0.00 feet

Figure 4.5. Study Area: Histogram Statistics

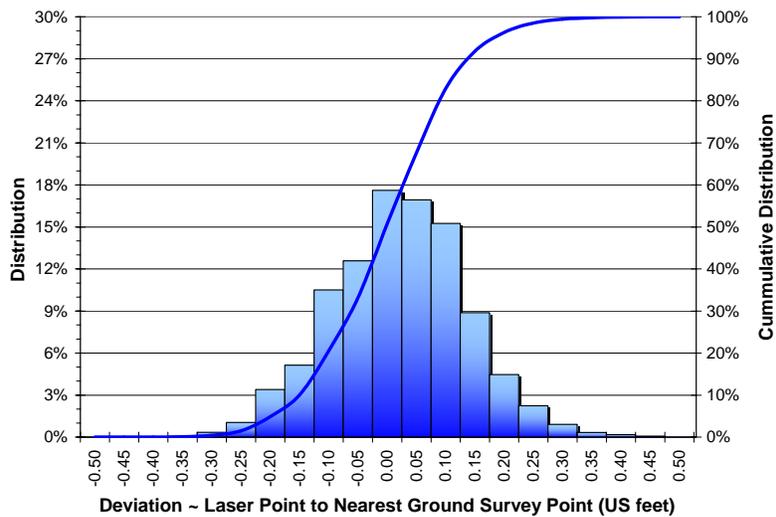
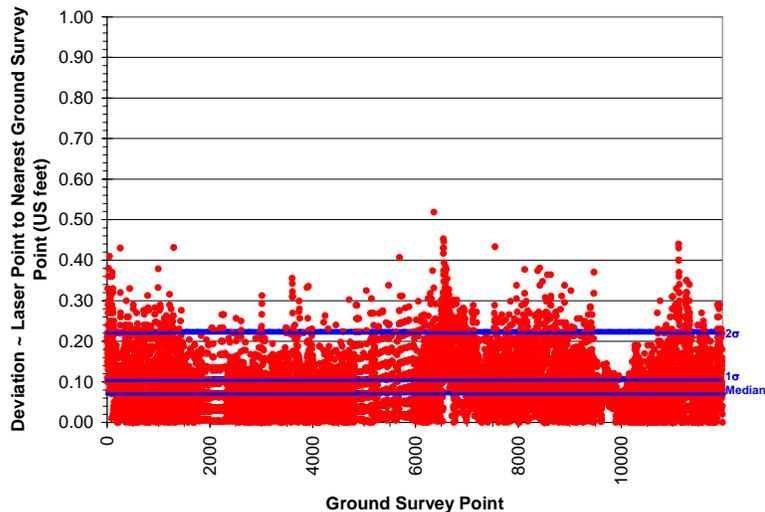


Figure 4.6. Study Area: Point Absolute Deviation Statistics



2008 Acquisition Area

The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. For the DOGAMI and ODF study areas acquired in 2008, 5,193 RTK points were collected. Accuracy statistics are reported in Table 4.3 and shown in Figures 4.7-4.8.

Table 4.3. Absolute Accuracy - Deviation between laser points and RTK survey points.

Sample Size (n): 5193	
Root Mean Square Error (RMSE): 0.13 feet	
Standard Deviations	Deviations
1 sigma (σ): 0.11 feet	Minimum Δz : -0.51 feet
2 sigma (σ): 0.27 feet	Maximum Δz : 0.84 feet
	Average Δz : -0.02 feet

Figure 4.7. Study Area: Histogram Statistics

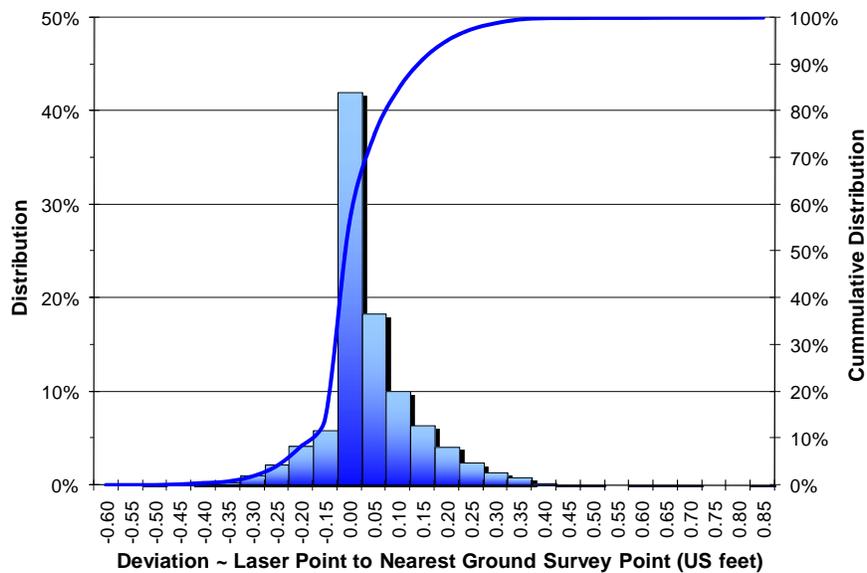
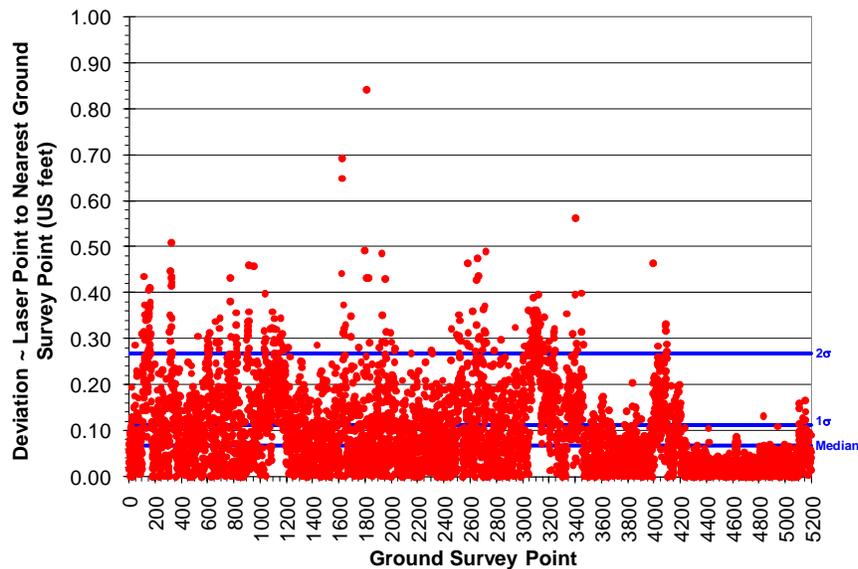


Figure 4.8. Study Area: Point Absolute Deviation Statistics

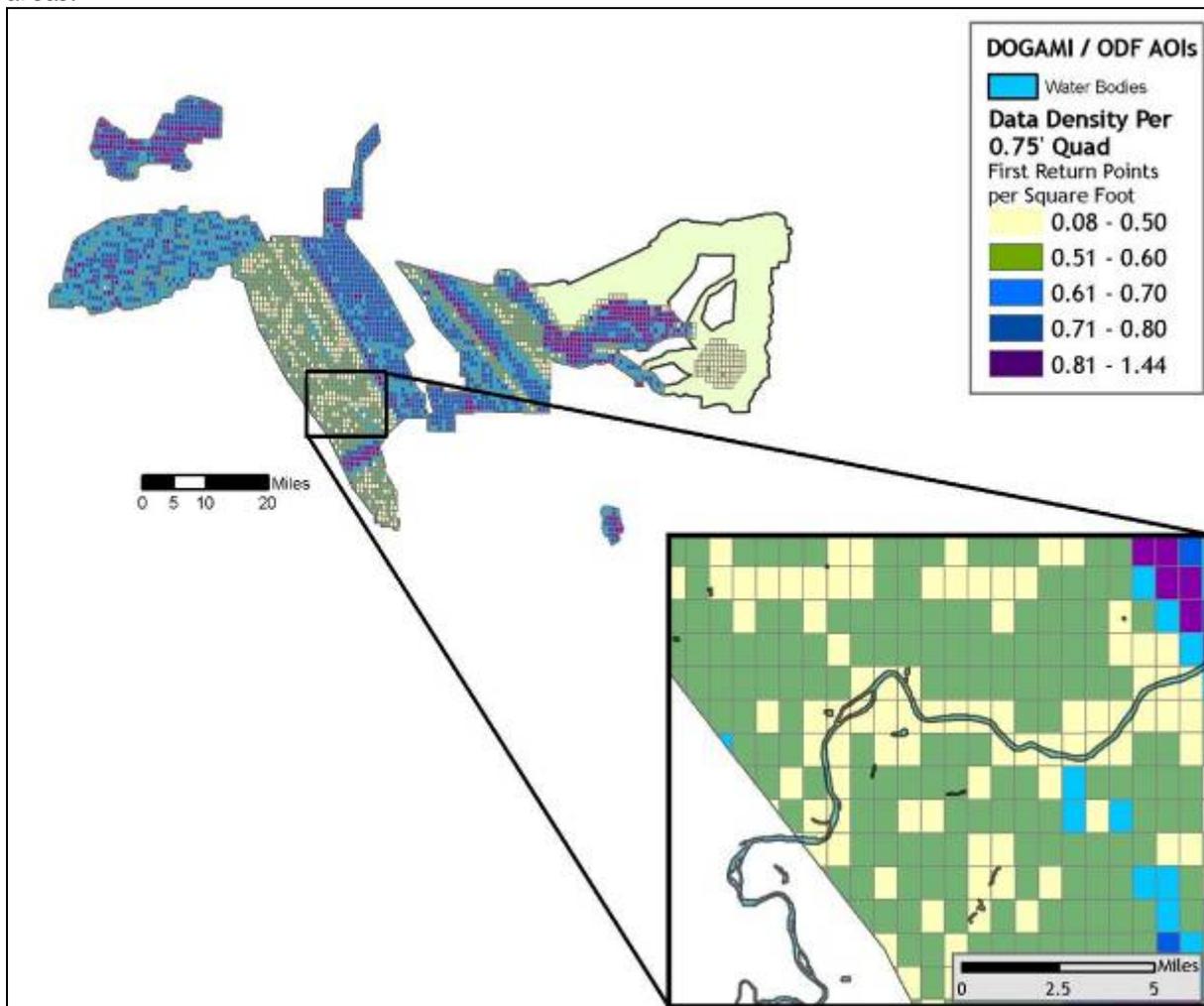


4.2 Data Density/Resolution

Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and lightly variable according to distributions of terrain, land cover and water bodies (Figure 4.9). Density histograms and maps (Figures 4.10-4.21) have been calculated based on first return laser point density and ground-classified laser point density (see Section 4.3 for discussion of density per AIO).

	Total Pulse Density	Ground Pulse Density
2007 ODF Data Acquisition Processing Complete	7.71 points per square meter 0.72 points per square foot	0.71 points per square meter 0.07 points per square foot
2007 DoGAMI Data Acquisition Processing Complete	6.90 points per square meter 0.64 points per square foot	1.28 points per square meter 0.12 points per square foot
2008 DoGAMI Data Acquisition Processing Complete	7.75 points per square meter 0.72 points per square foot	0.76 points per square meter 0.07 points per square foot

Figure 4.9. Illustration of the location of water bodies and the corresponding lower-density data areas.



4.2.1 First Return Laser Pulses per Square Foot

Figure 4.10. Histogram of first return laser point data density in both of ODF's AOIs, per 0.75' USGS Quad.

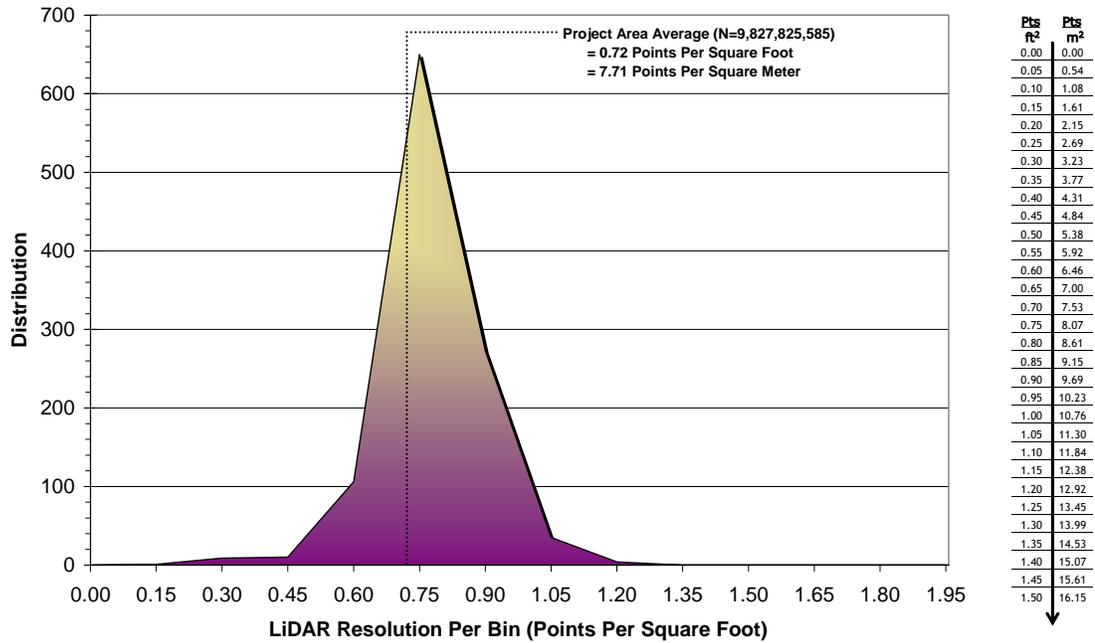


Figure 4.11. Image shows first return laser point data density in both of ODF's AOIs, per 0.75' USGS Quad.

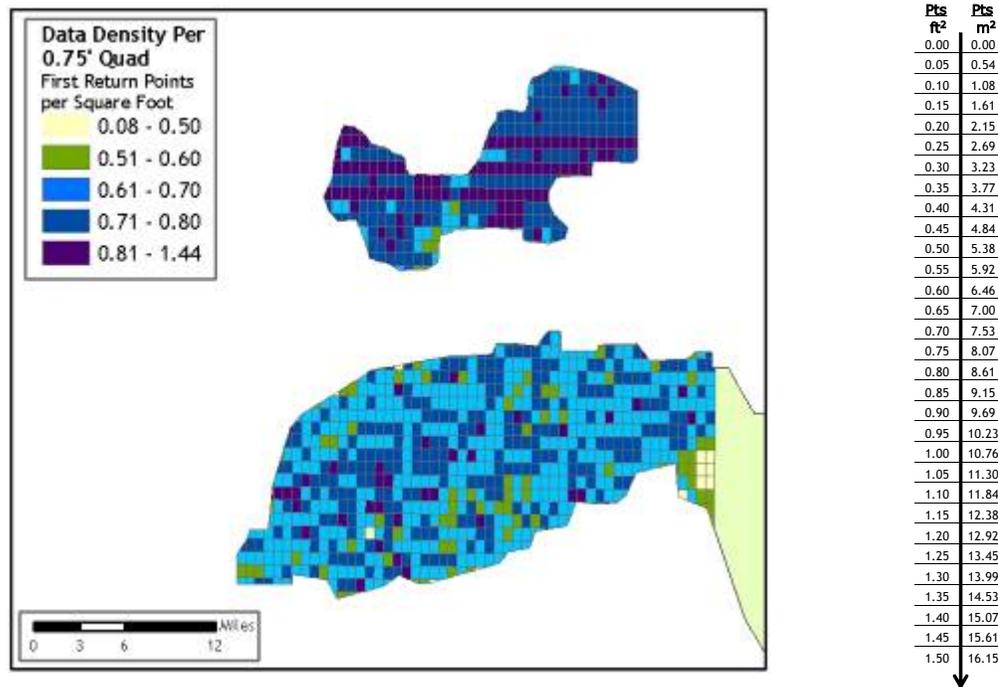


Figure 4.12. Histogram of first return laser point data density in all Portland Area quads acquired in 2007, per 0.75' USGS Quad.

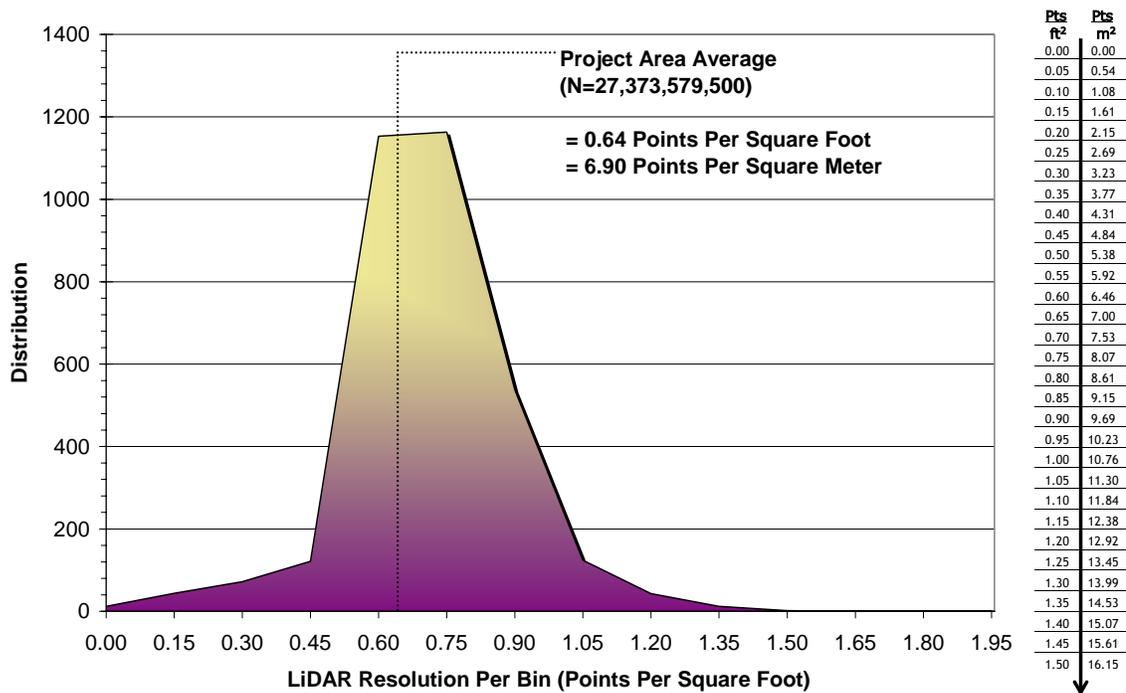


Figure 4.13. Image shows first return laser point data density in all Portland Area quads acquired in 2007, per 0.75' USGS Quad.

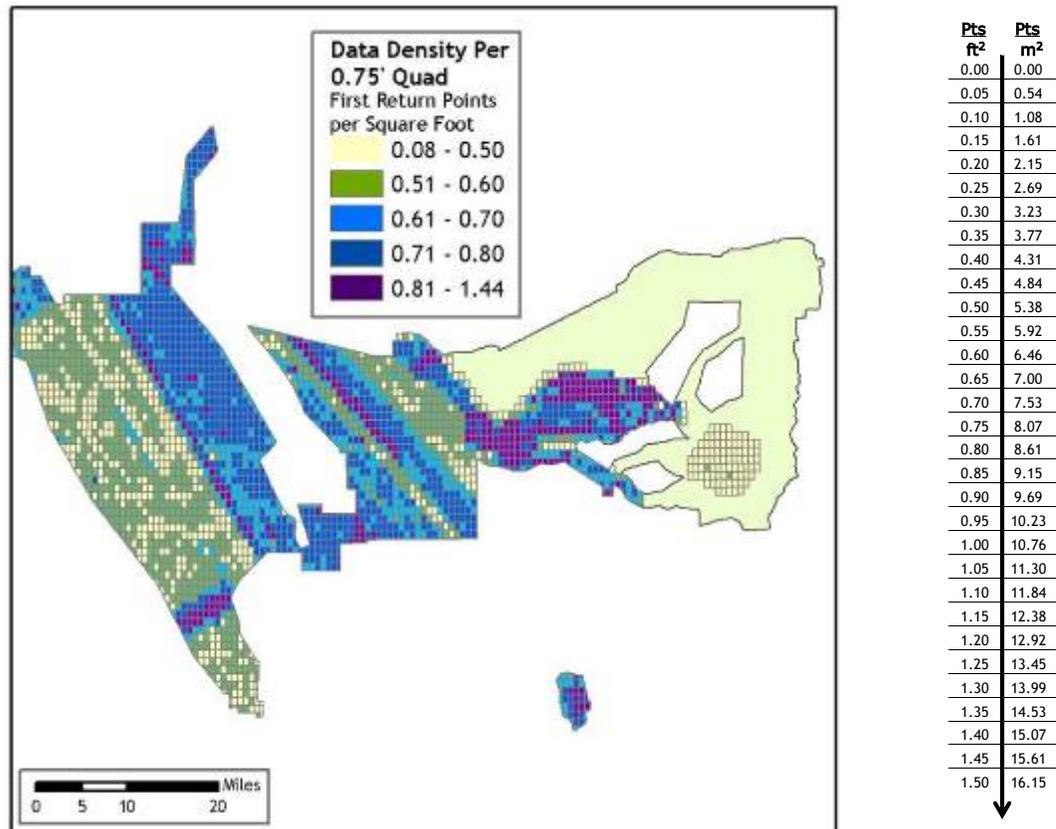


Figure 4.14. Histogram of first return laser point data density in all Portland Area quads acquired in 2008, per 0.75' USGS Quad.

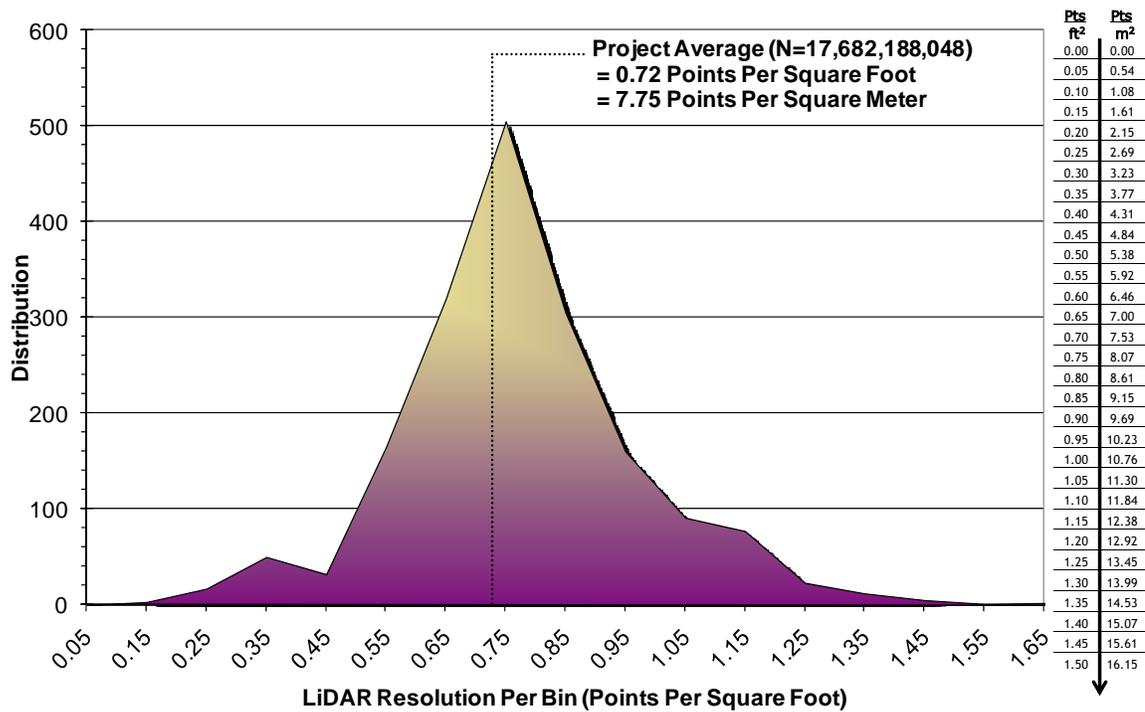
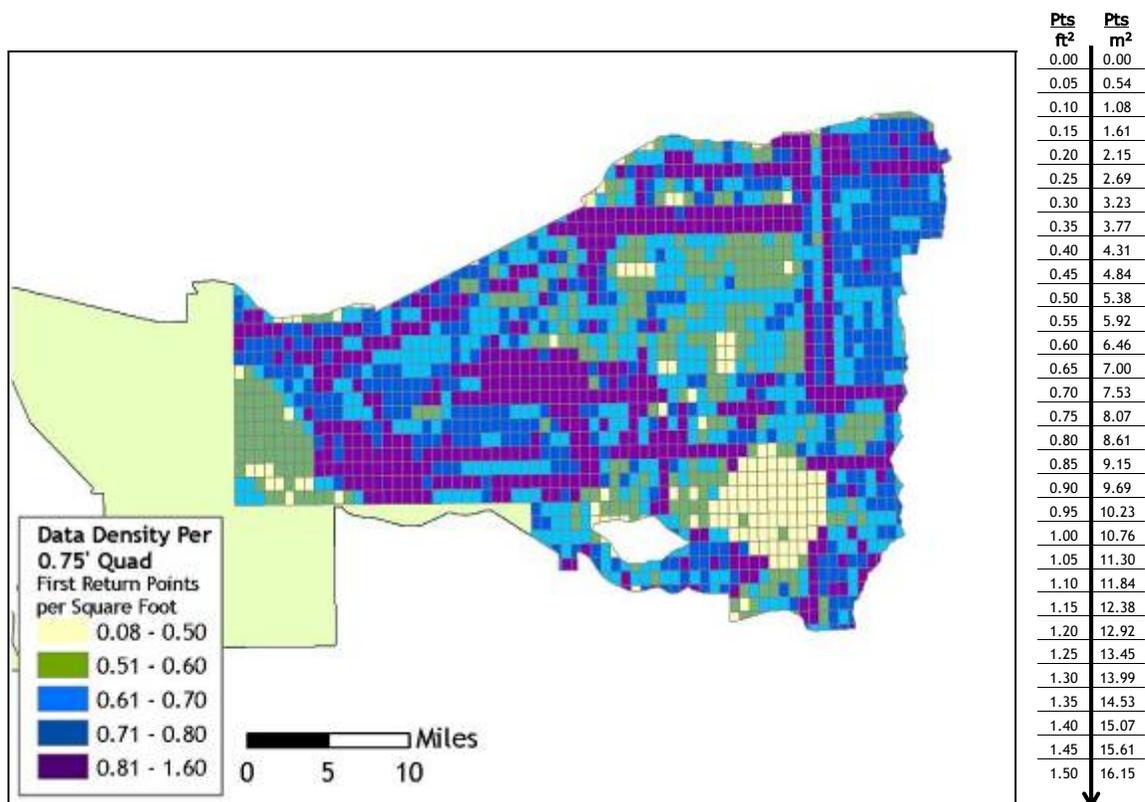


Figure 4.15. Image shows first return laser point data density in all Portland Area quads acquired in 2008, per 0.75' USGS Quad.



4.2.2 Classified Ground Points per Square Foot

Ground classifications are derived from ground surface modeling. Supervised classifications were performed by reseeded of the ground model where it is determined that the ground model has failed, usually under dense vegetation and/or at breaks in terrain, steep slopes and at bin boundaries.

Figure 4.16. Histogram of ground-classified laser point data density in both ODF's AOIs, per 0.75' USGS Quad.

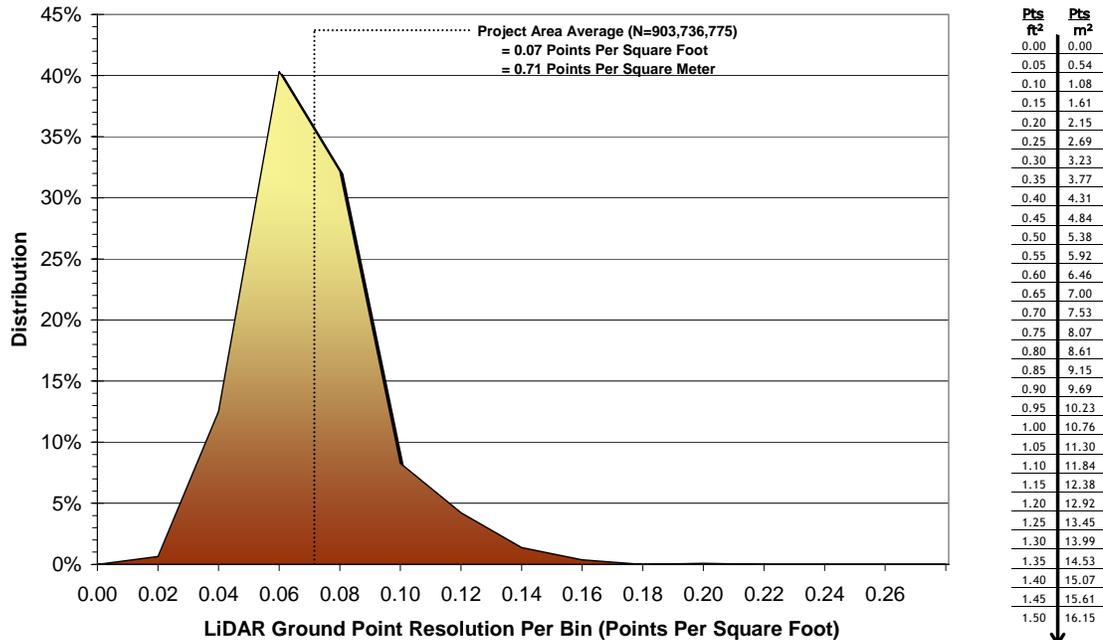


Figure 4.17. Image shows ground-classified laser point data density per 0.75' USGS Quad in both ODF's AOIs.

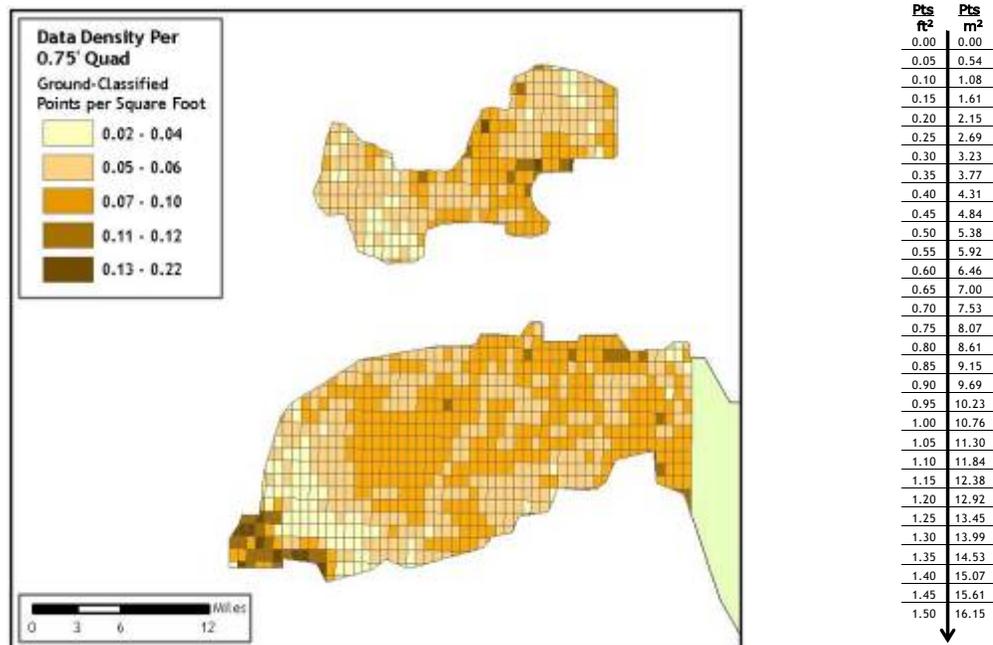


Figure 4.18. Histogram of ground-classified laser point data density in all Portland Area data acquired in 2007, per 0.75' USGS Quad.

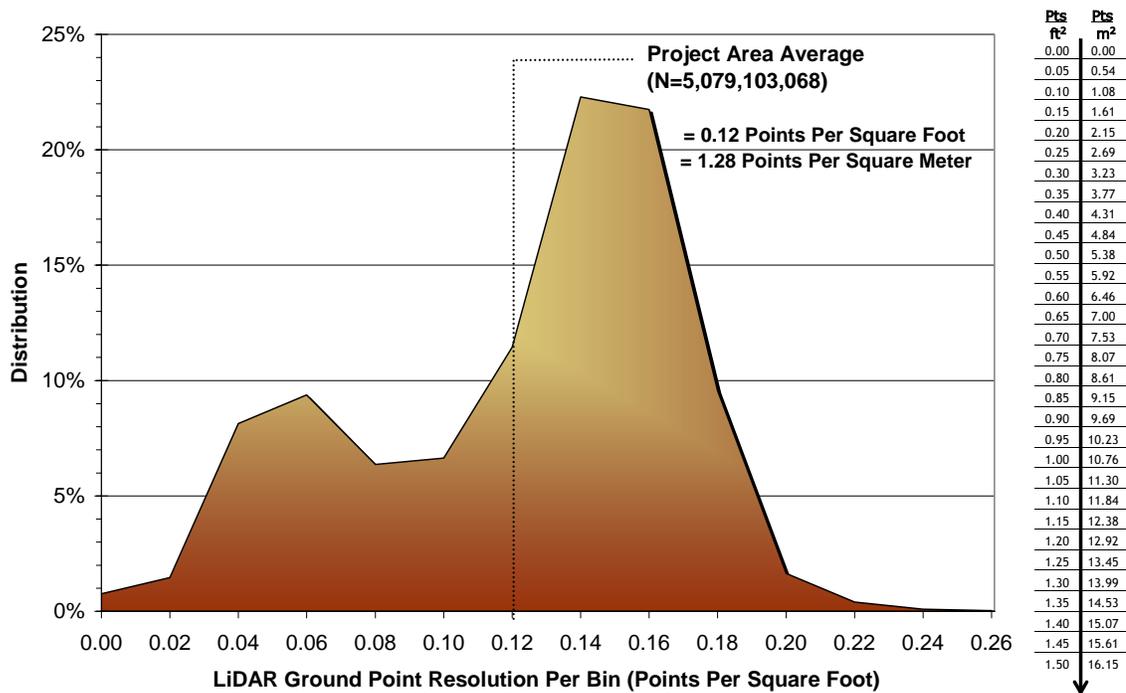


Figure 4.19. Image shows ground-classified laser point data density in all Portland Area data acquired in 2007, per 0.75' USGS Quad.

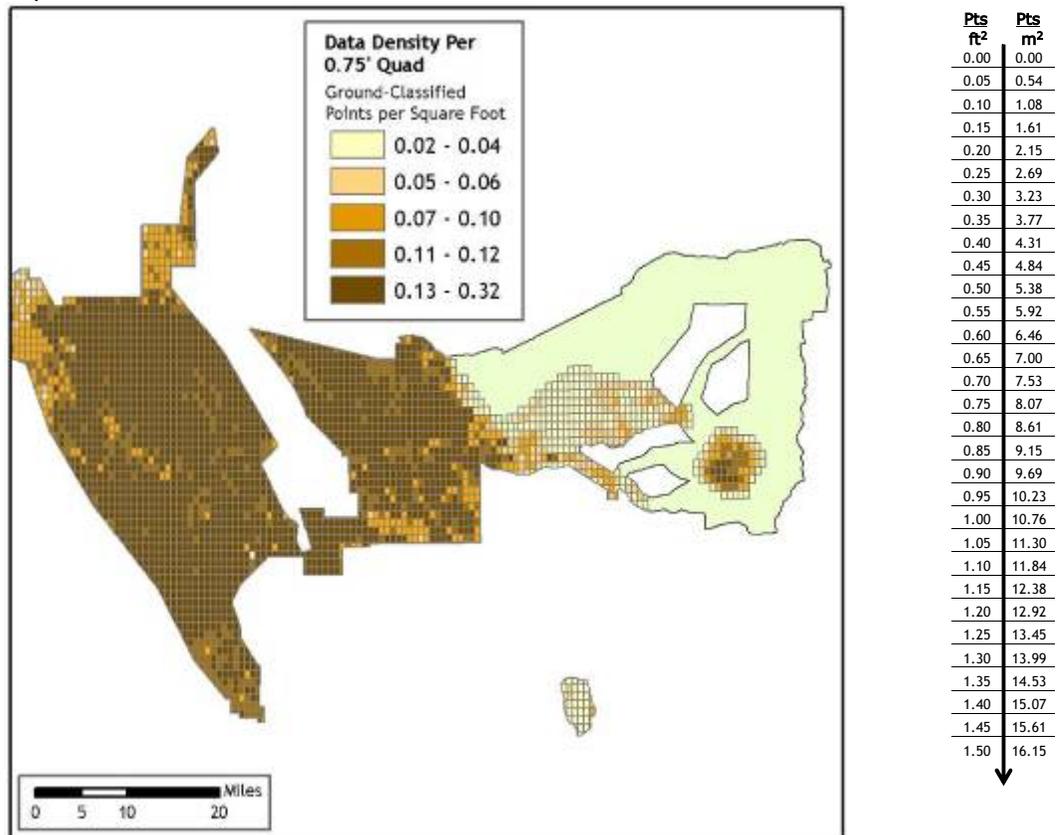


Figure 4.20. Histogram of ground-classified laser point data density in all Portland Area data acquired in 2008, per 0.75' USGS Quad.

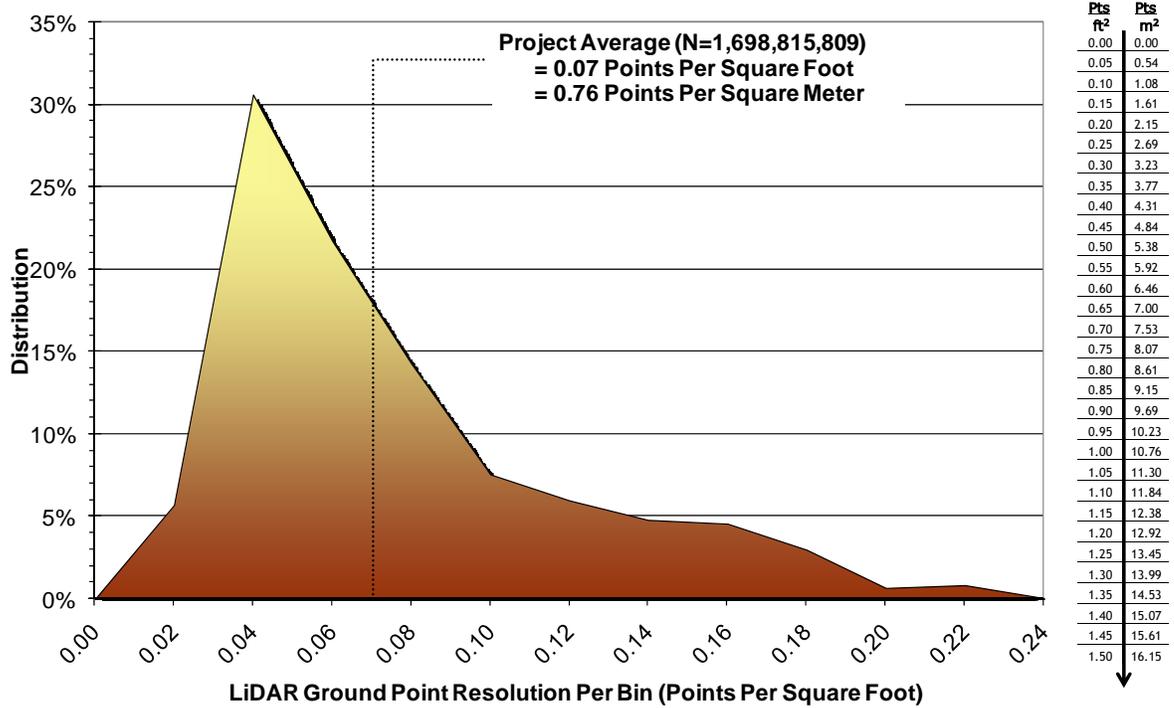
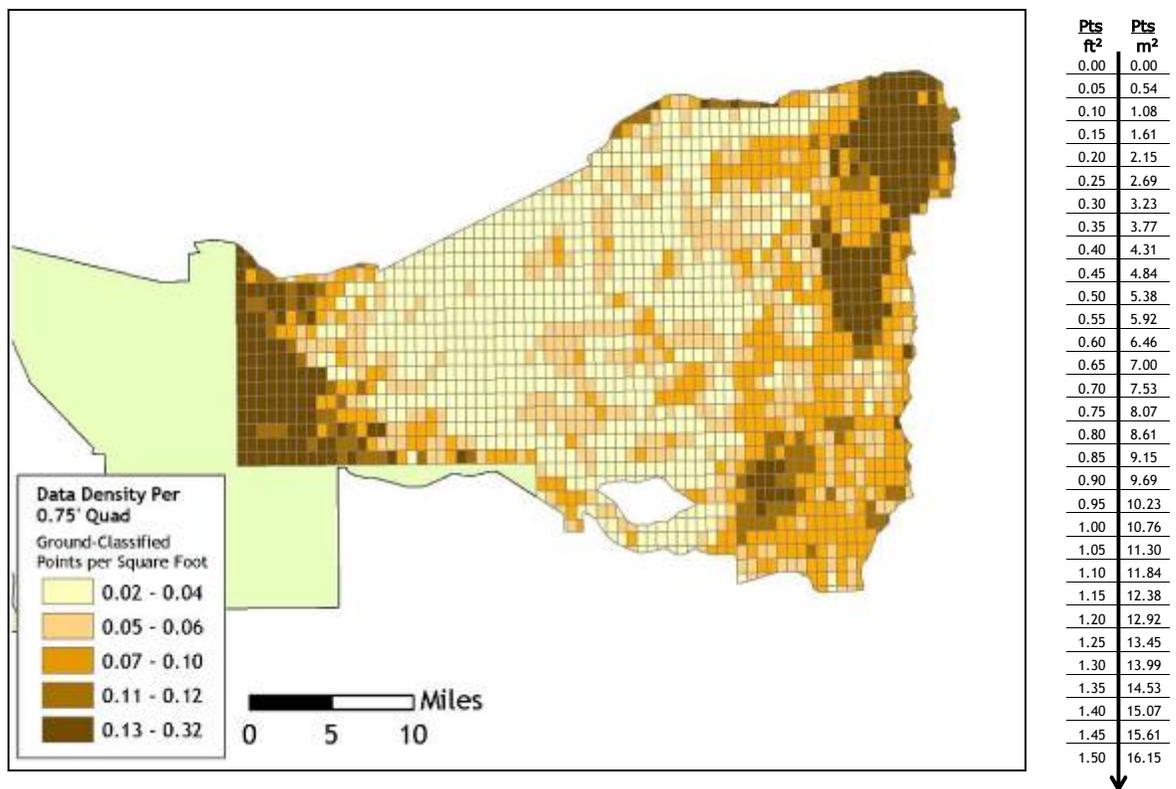


Figure 4.21. Image shows ground-classified laser point data density in all Portland Area data acquired in 2008, per 0.75' USGS Quad.



4.3 Data Density/Resolution per AOI

Table 4.4. Average Pulse Densities per AOI in the DOGAMI/ODF Study Areas.

AOI	Name	Average Pulse Density (ft)	Average Pulse Density (m)
1	Portland	0.62	6.66
2	ODF	0.72	7.71
3	Upper Sandy River	0.70	7.56
4	Collawash	0.69	7.46
5	Lower Sandy River	0.78	8.38
6 & 7	Mt. Hood	0.27	2.91
8	Bull Run	0.83	8.92
9	Hood / Gorge	0.76	7.75

4.3.1 Portland AOI

The Portland AOI was acquired with both an Optech 3100 and a Leica ALS50 LiDAR system, resulting in different acquisition densities per laser (Figure 4.22). In areas of flightline overlap, higher data densities occur (Figure 4.23). The average pulse density for the Portland AOI is 0.62 pulses per square foot (6.66 pulses per square meter).

Figure 4.22. Illustration of difference in data density between two different LiDAR systems used.

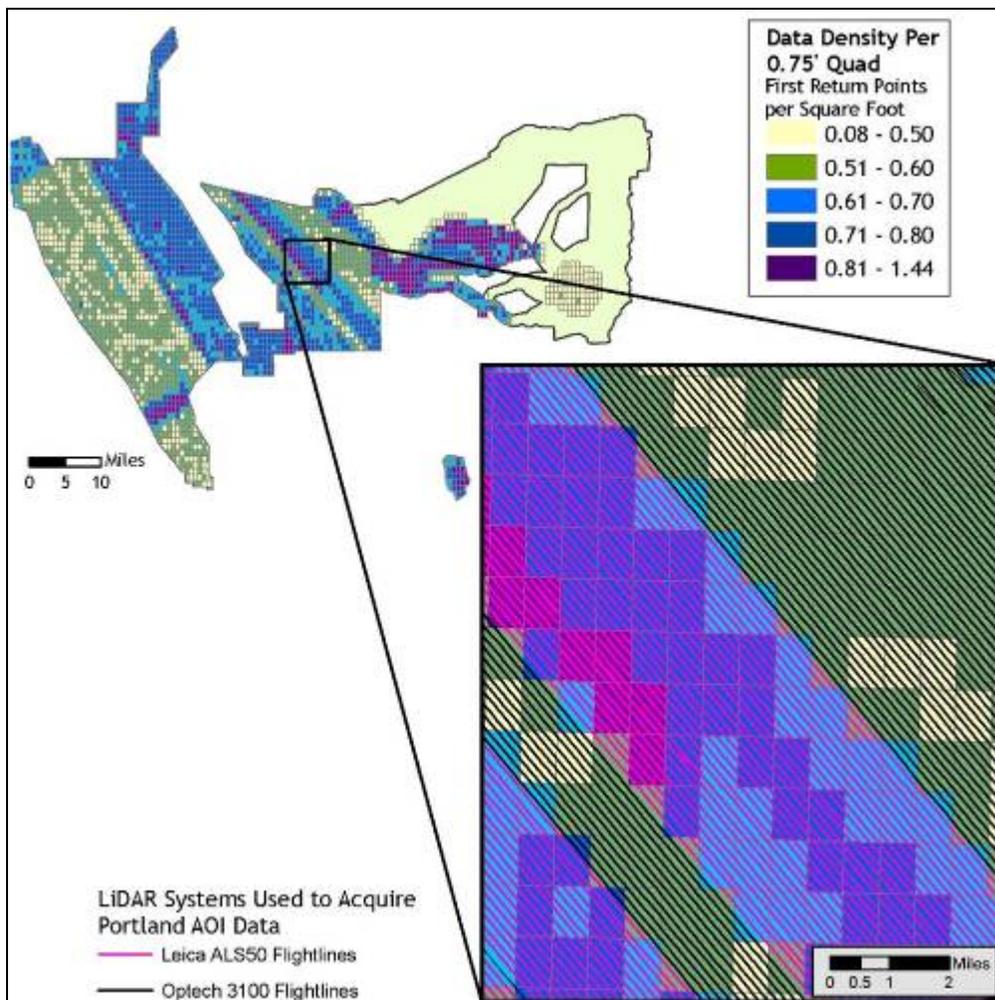
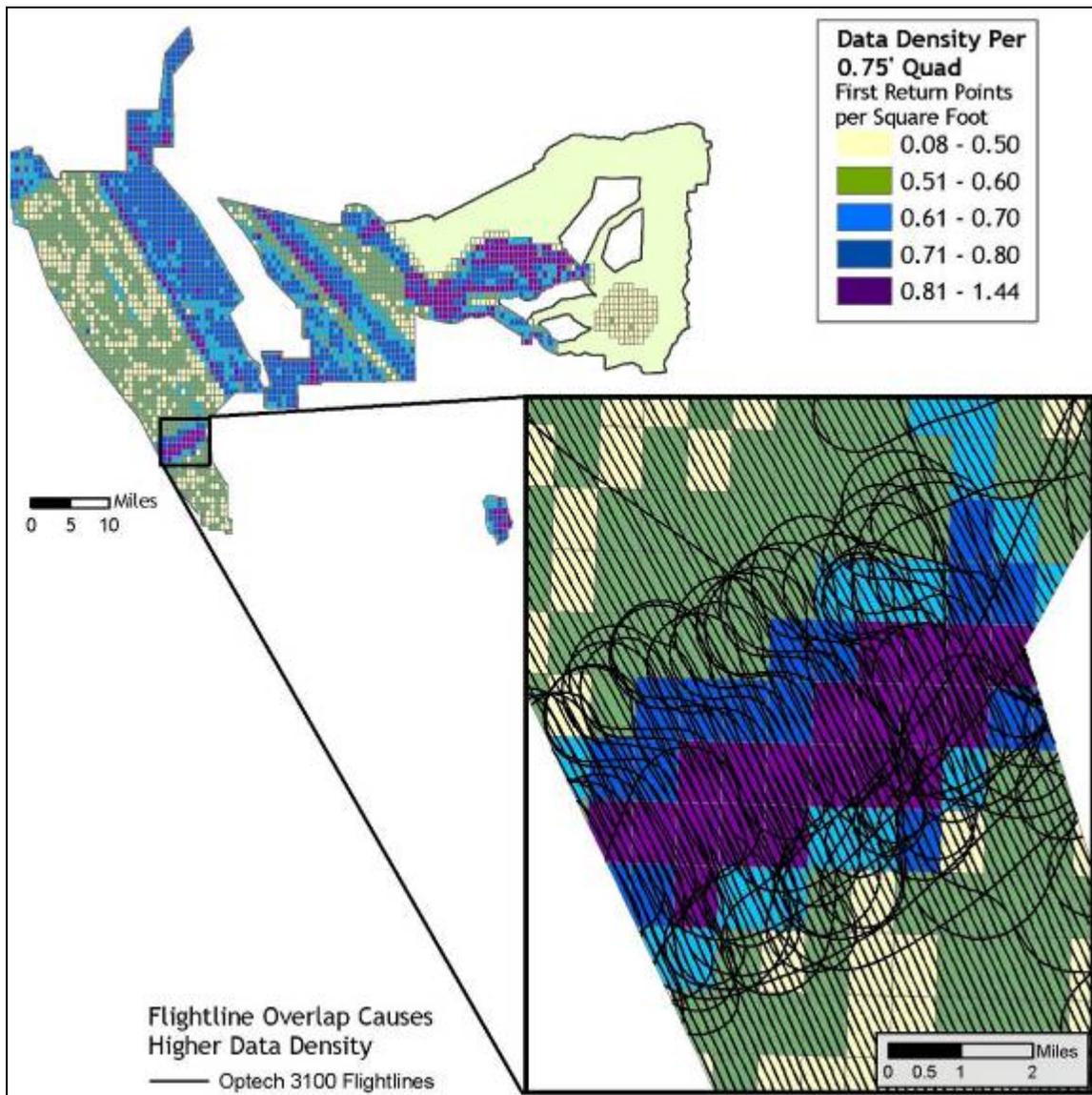


Figure 4.23. Illustration of higher data density in areas of overlapping flightlines.



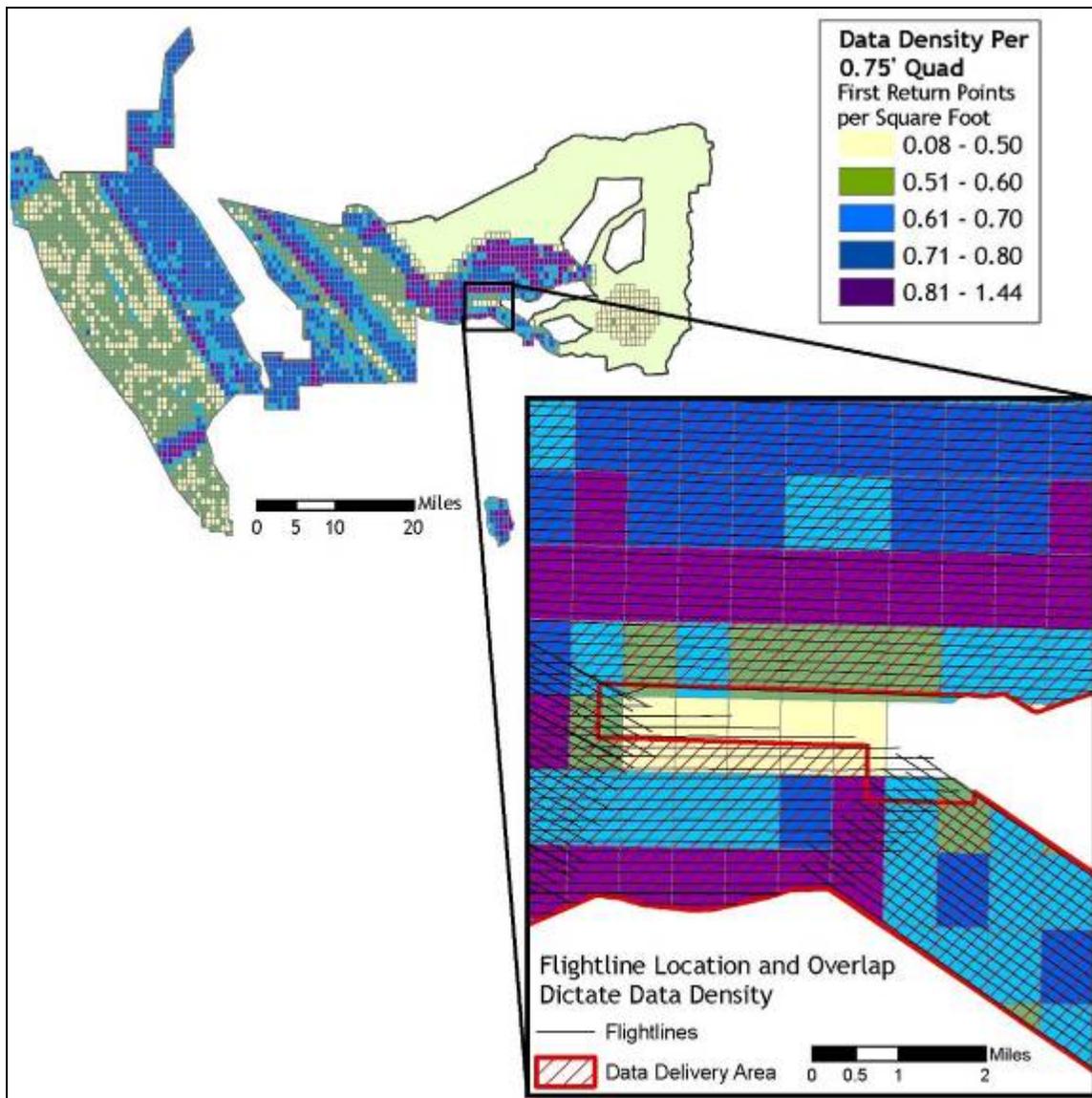
4.3.2 ODF AOI

The average pulse density for the ODF AOI is 0.72 pulses per square foot (7.71 pulses per square meter). See Figure 4.11 in Section 4.2.1 for illustration of density coverage in the ODF study area.

4.3.3 Upper Sandy / Bull Run AOIs

Due to the shapes and locations of the Upper Sandy and Bull Run study areas, an area of incomplete data coverage occurred between the two acquisition polygons (**Figure 4.24**), resulting in a lower data density. The average pulse density for the Upper Sandy AOI is 0.70 pulses per square foot (7.56 pulses per square meter). The average pulse density for the Bull Run AOI is 0.83 pulses per square foot (8.92 pulses per square meter).

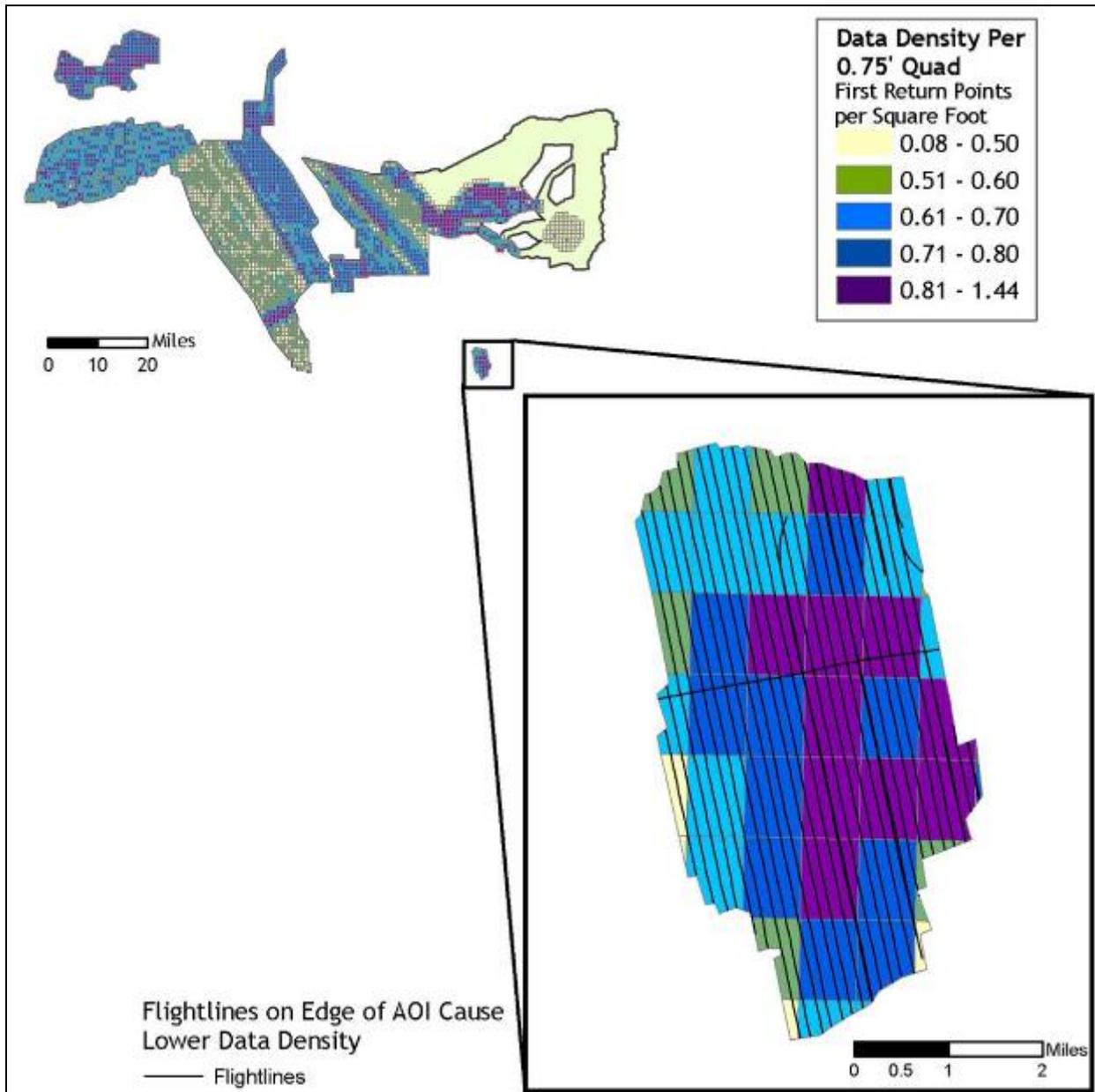
Figure 4.24. Illustration of lower-density data blocks caused by sparse or no flightlines.



4.3.4 Collawash AOI

The Collawash study area was an isolated survey, and as a result, the edges of the AOI experienced a lower data density due to single flightline edges. The average pulse density for the Collawash AOI is 0.69 pulses per square foot (7.46 pulses per square meter).

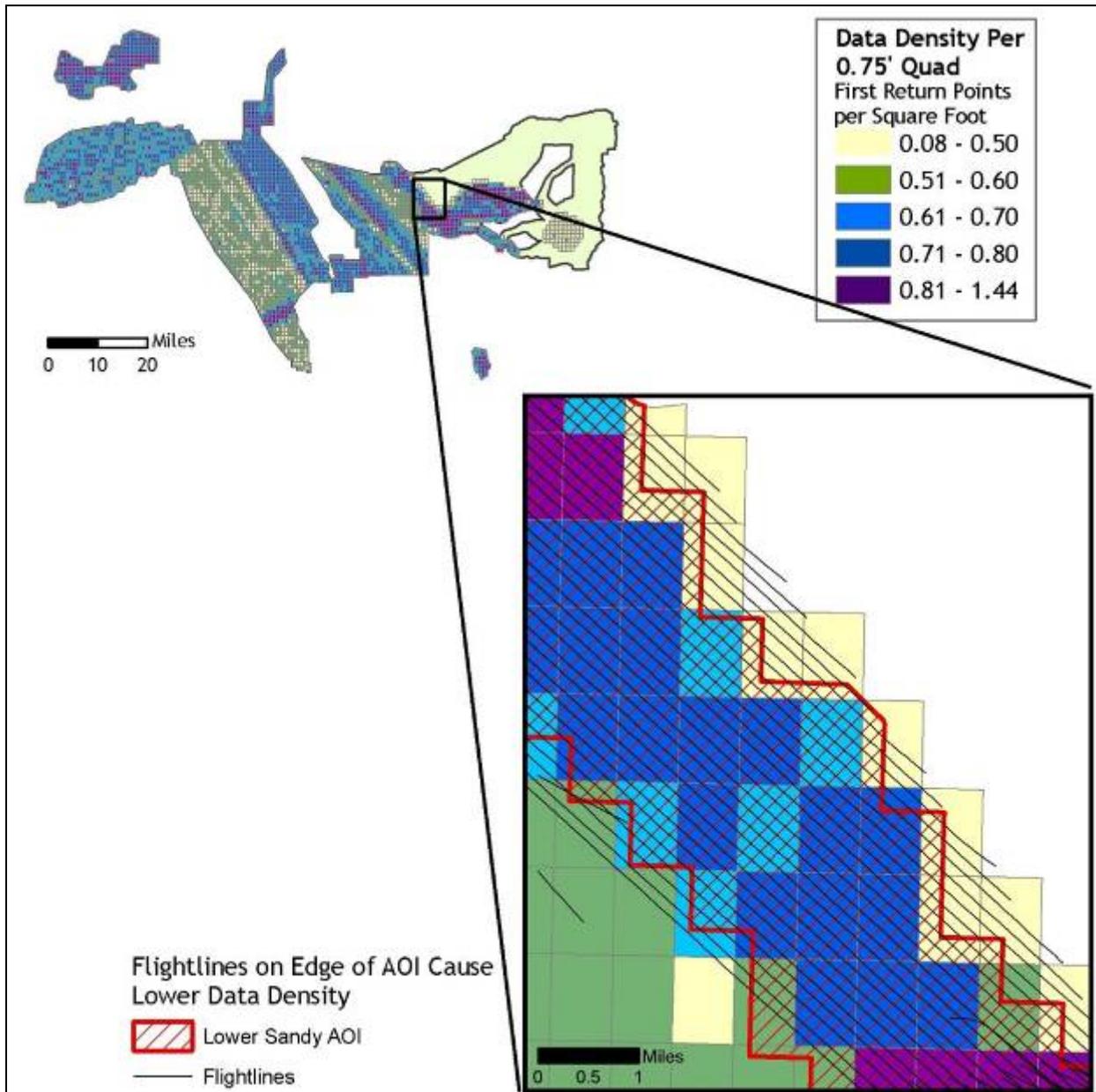
Figure 4.25. Image illustrating the lower data density caused by edge flightlines along the border of the Collawash study area.



4.3.5 Lower Sandy AOI

The lower sandy survey is on the edge of the acquired data; therefore, the edge data blocks experience a lower density due to single flightline edges. The average pulse density for the Lower Sandy AOI is 0.78 pulses per square foot (8.38 pulses per square meter).

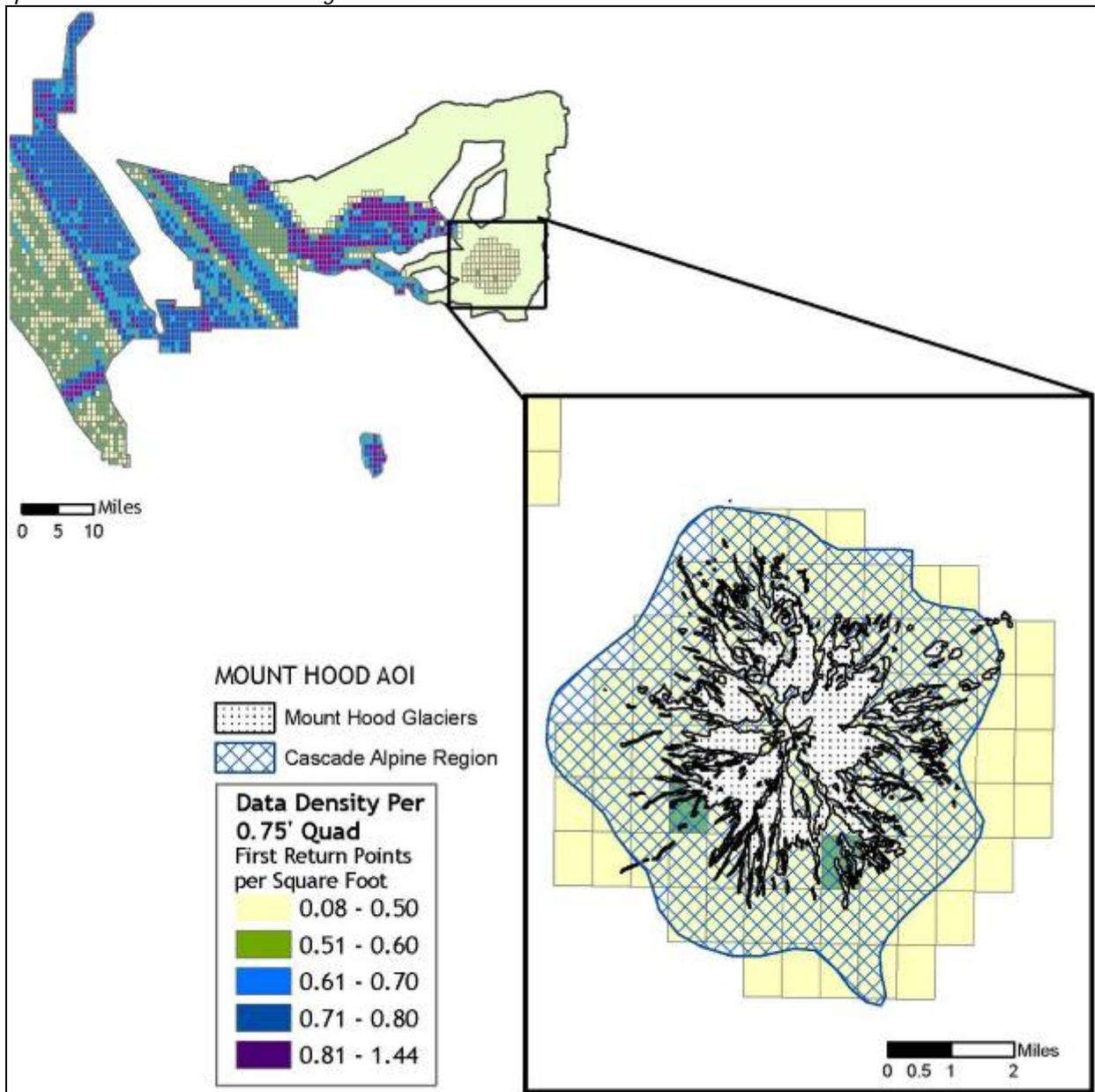
Figure 4.26. Image illustrating the lower data density caused by edge flightlines along the border of the Lower Sandy study area.



4.3.6 Mount Hood AOI

The Mount Hood AOI data has a lower data density than the project average; this was due to the data collection specifications tailored for high-relief (see Table 2.1). As the laser range increases, the available pulse rate frequency decreases. The survey aircraft cannot terrain follow Mount Hood easily or safely, and therefore, requires a larger operational range. Lower pulse rates result, causing lower data densities. The average pulse density for the Mount Hood AOI is 0.27 pulses per square foot (2.91 pulses per square meter).

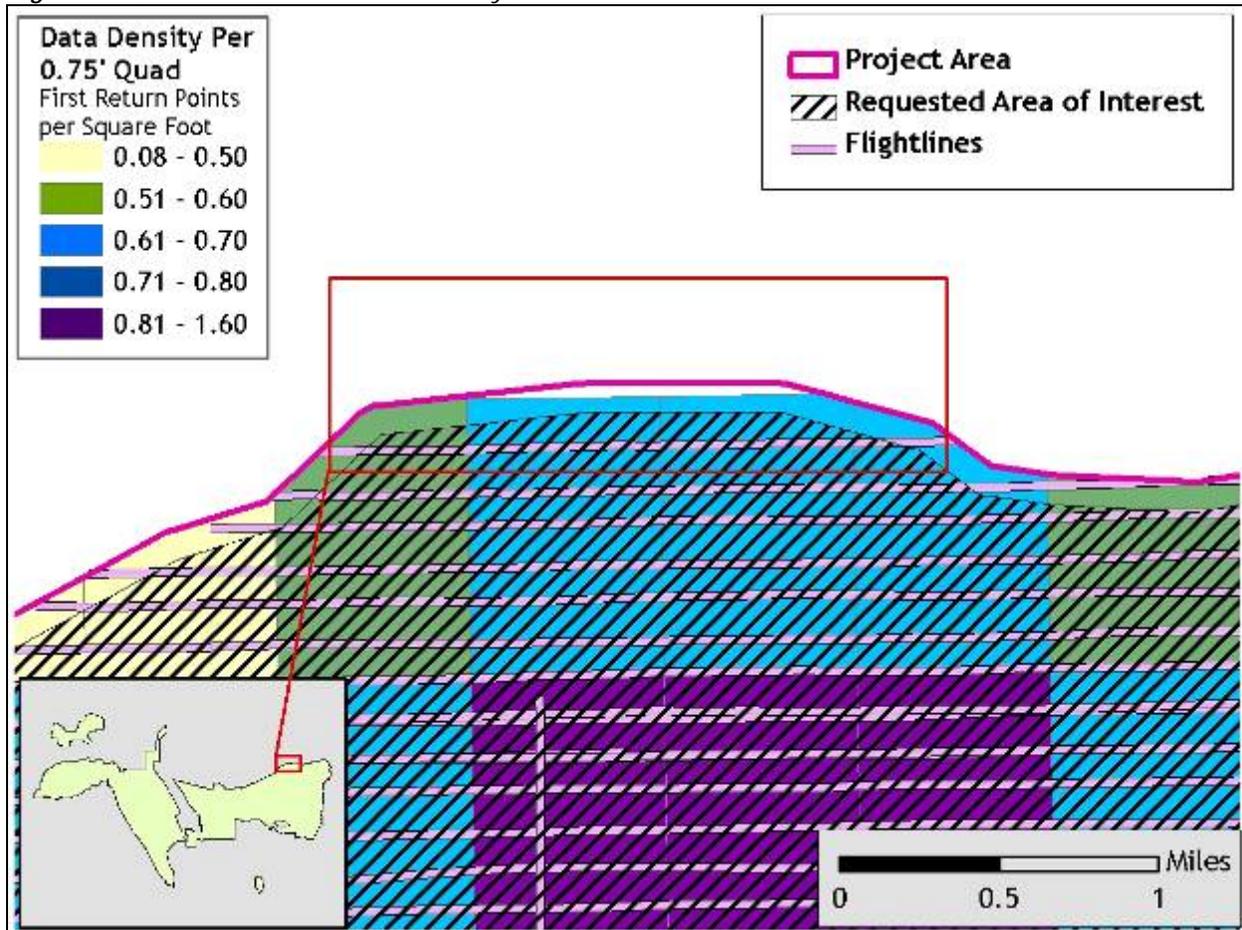
Figure 4.27. Illustration of lower data density in the Mt. Hood AOI as a result of acquisition specifications and Mt. Hood's glaciers.



4.3.7 Columbia River Gorge AOI

The northern border of the Gorge portion of the Portland AOI coincides with the Columbia River. Owing to the variable response of laser returns over open water, the point density on the northern edge of the study area is lower than the project average. In some cases, no returns were captured over the river, leaving a gap in the expected data collection border; however, the data collected still fully covers the area of interest requested by the client.

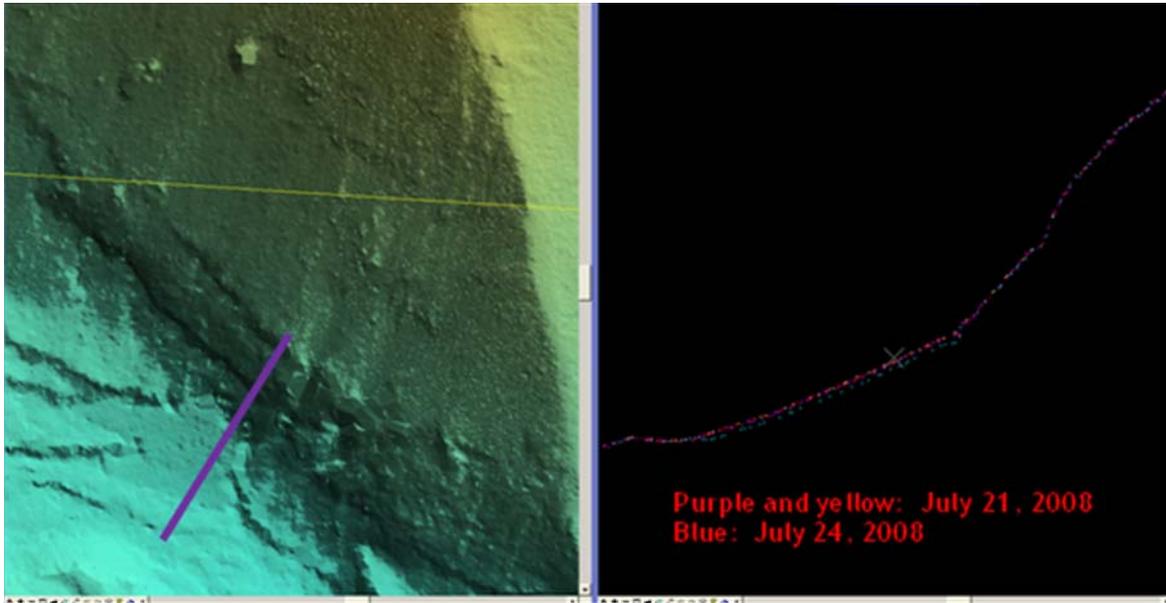
Figure 4.28. Illustration of lower density data over the Columbia River.



5. Mt. Hood / Columbia River Gorge Acquisition Discussion

The 2008 LiDAR acquisition follows a record year for snowfall in the Mt. Hood region. Snow persists in this dataset in sheltered canyons, heavily timbered acreage, and lee slopes. **Figure 5.1**, below, depicts a cross-section above timberline on the southeast flank of Mt. Hood. The image to the right is colored by flightline. Pink and yellow point data were collected July 21, 2008, while the blue data were collected July 24. The point data are in agreement on upper and exposed surfaces. Between these surfaces, an apparent snow-filled swale exhibits elevation displacement. Elevation differences between the two dates (approximately 4 cm) is attributed to snowmelt.

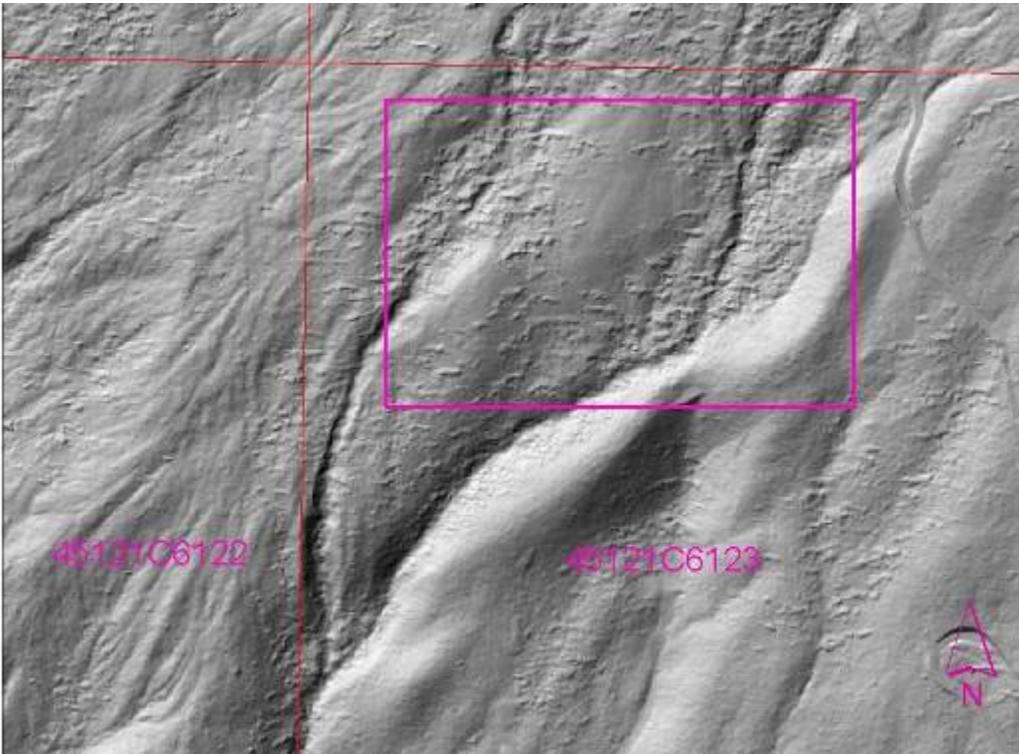
Figure 5.1. Snow melt in sheltered canyon.



Snow is present in timbered areas, manifesting as lobed surface features. **Figure 5.2** illustrates snow features in a forested area near Timberline Ski Area.

Figure 5.2. Lobed snow features on forested lee slopes. a. Bare-earth DEM. b. Highest Hit DEM.

a.



b.



Artifacts resulting from the difference in acquisition dates are evident in the data. The data from 2007 and 2008 surveys agree well on firm permanent surfaces (Figure 5.3). However, in some instances, topographic change is marked between the two acquisition periods. Figure 5.4 illustrates the presence of a new surface feature at the south-eastern end of a parking lot servicing Mt. Hood Meadows ski area.

Figure 5.3. Cross section spanning 2007 and 2008 datasets (border demarcated by yellow line) on road surface near Mt. Hood Meadows ski area.

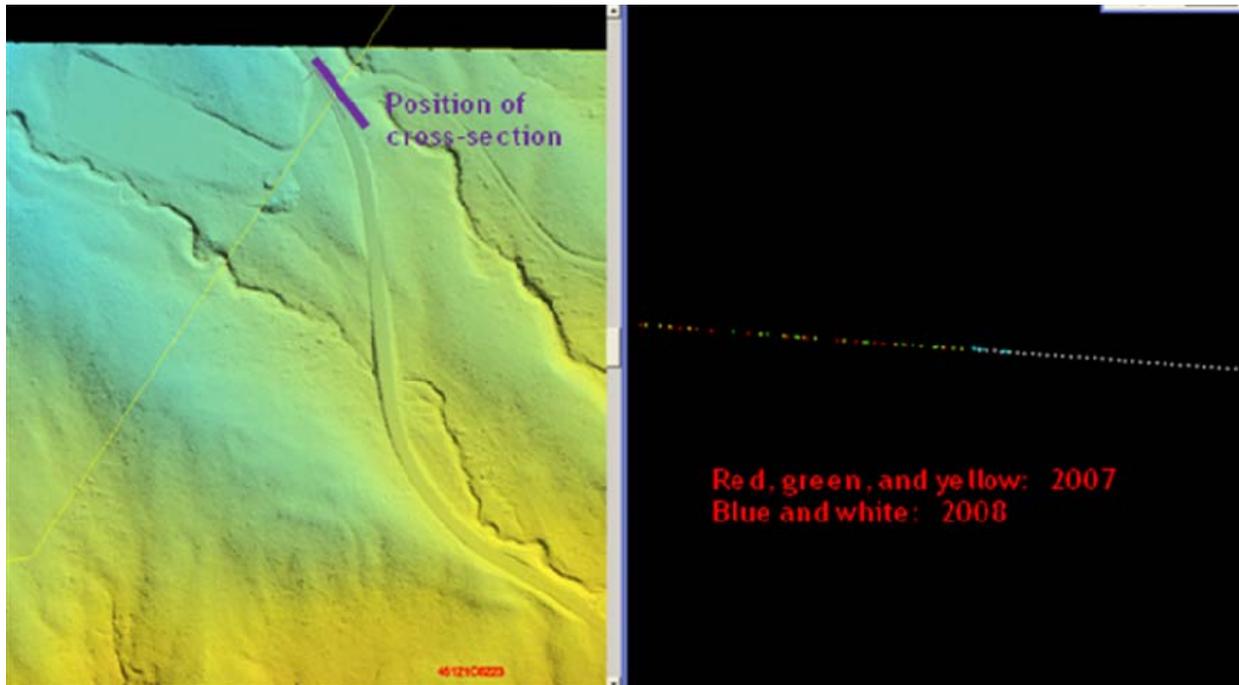


Figure 5.4. Cross-section illustrating new surface feature not present in the 2007 dataset

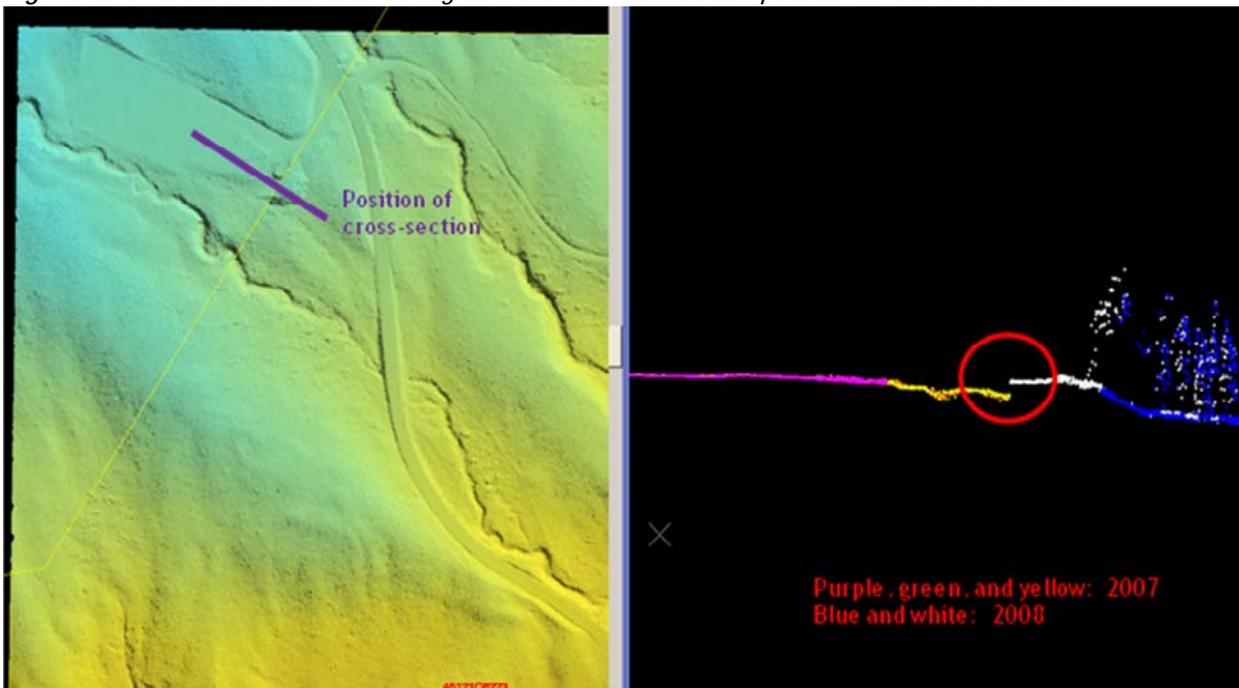
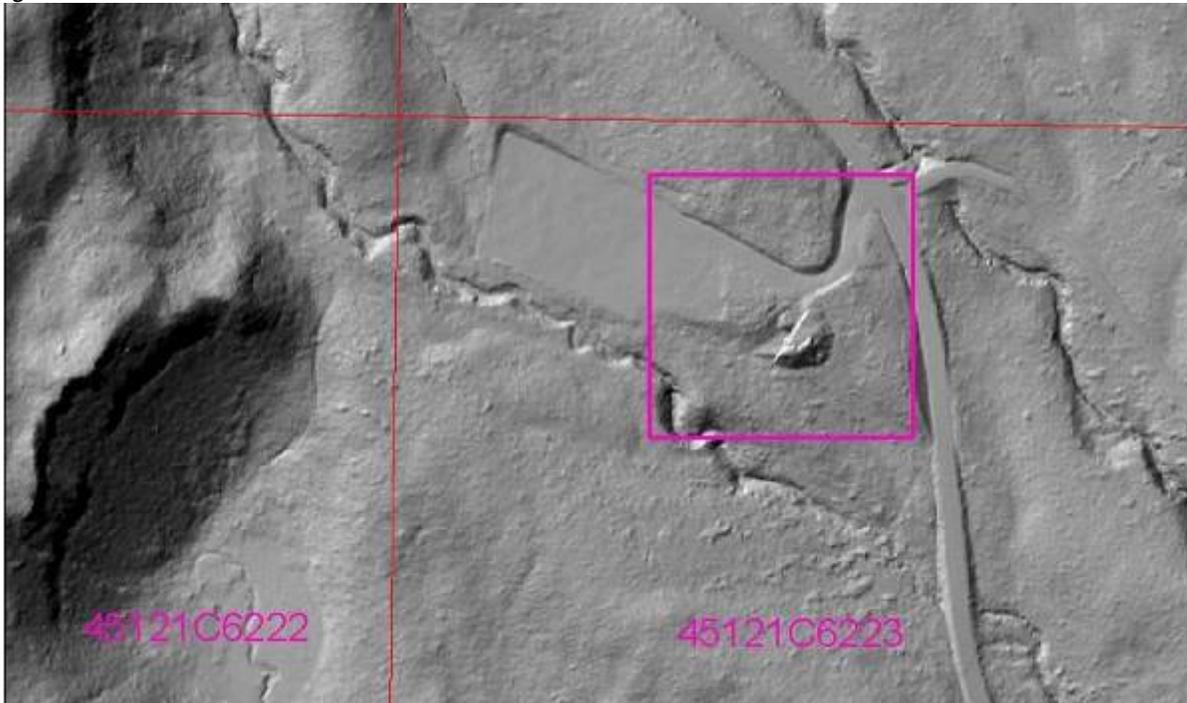
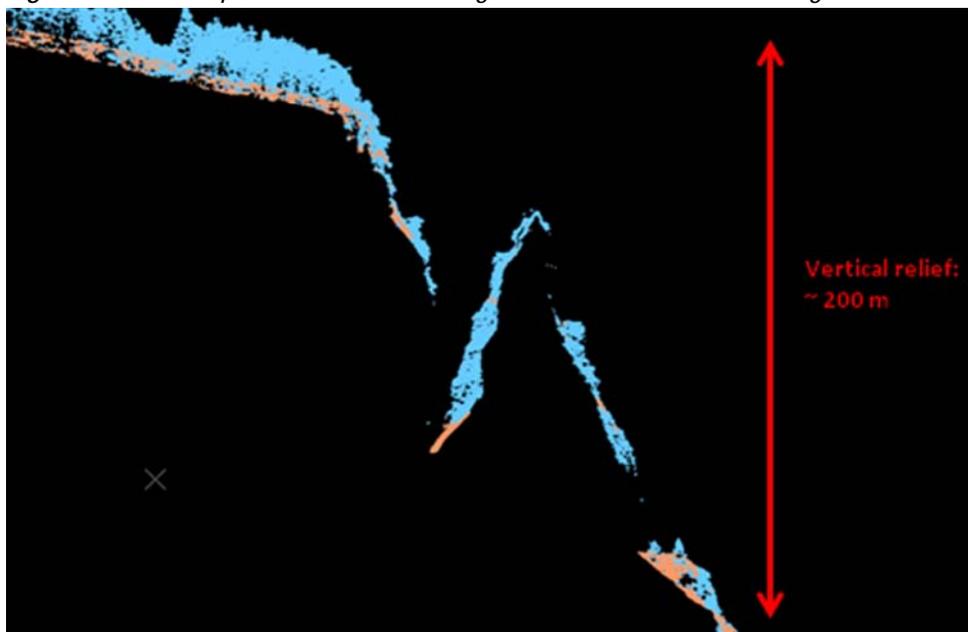


Figure 5.5. Hillshade of the bare earth DEM surface for the area in the discussion above.



Laser shadowing occurs when topographic or feature orientation relative to scan angle results in the occlusion of surface features. In areas of exceptional topographic variability, such as the ridgeline in the figure below (Tile 45121F7402), laser shadowing can result in voids in the LiDAR derived ground model. While flight planning attempts to minimize this acquisition artifact, terrain challenges present in the Columbia River Gorge prevented their elimination.

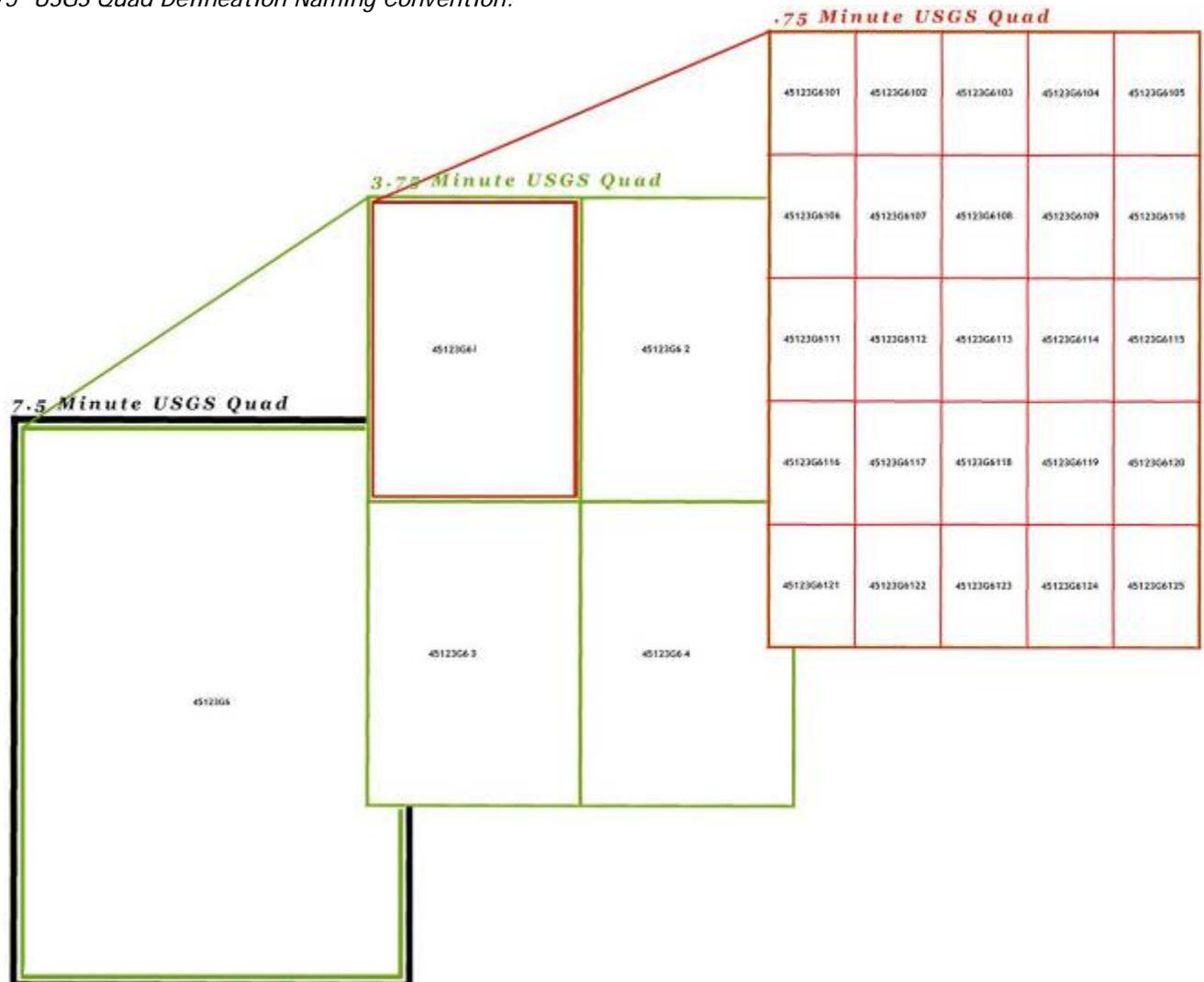
Figure 5.6. Example of laser shadowing in the Columbia River Gorge.



6. Deliverables

All Deliveries of DOGAMI and ODF Data conform to the following tiling scheme:

Figure 5.1. 0.75' USGS Quad Delineation Naming Convention.



6.1 Point Data (per 0.75' USGS Quad)

Data Fields: Number, X, Y, Z, Intensity, ReturnNumber, NumReturns, ScanDirection, EdgeOfFlightLine, Class, ScanAngleRank, FileMarker, UserBitField, GPSTime

- LAS v 1.1 Format
- ASCII Format
- Smoothed Best Estimate of Trajectory Point Files in ASCII format

6.2 Vector Data

- Total Area Flown
 - 7.5-minute quadrangle delineation in shapefile format
 - 0.75-minute quadrangle delineation in shapefile format (See **Figure 5.1** below for illustration)

6.3 Raster Data

- ESRI GRID of Bare Earth Modeled LiDAR data Points (3-foot resolution) delivered in 7.5' USGS Quad Delineation
- ESRI GRID of Above Ground Modeled LiDAR data Points (3-foot resolution) delivered in 7.5' USGS Quad Delineation
- Intensity Images in GeoTIFF format (1.5-foot resolution) delivered per 0.75' Quad

6.4 Data Report

- Full Report containing introduction, methodology, and accuracy.
 - Word Format (*.doc)
 - PDF Format (*.pdf)

6.5 Datum and Projection

The data were processed as ellipsoidal elevations and required a Geoid transformation to be converted into orthometric elevations (NAVD88). In TerraScan, the NGS published Geoid03 model is applied to each point. The data were processed using meters in the Universal Transverse Mercator (UTM) Zone 10 and NAD83 (CORS96)/NAVD88 datum and converted to the respective projections for each data set as specified below.

- ODF AOIs are delivered in Oregon Lambert, EPSG 2992, with horizontal units in International Feet and vertical units in US Survey Feet, in the NAD83/NAVD88 datum (Geoid 03).
- All other AOIs are delivered in Oregon State Plane North, with horizontal units in International Feet and vertical units in US Survey Feet, in the NAD83 HARN/NAVD88 datum (Geoid 03).

7. Selected Images

(Edit by PSLC: To reduce this report to 10 MB, All figures in this section have been omitted. To get a full report including these images please go to <http://pugetsoundlidar.ess.washington.edu/lidardata/flighttrajectory.html> and look for 2007-2008 Oregon LiDAR Consortium Project)

8. 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.

2-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set.

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.

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

Pulse Returns: For every laser emitted, the Leica ALS 50 Phase II system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest 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.

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).

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

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

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

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.

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

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

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is 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.

9. Citations

Soininen, A. 2004. TerraScan User's Guide. Terrasolid.