LIDAR REMOTE SENSING METHODOLOGY

DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
SOUTHWEST WASHINGTON STUDY AREA

Prepared by Watershed Sciences on May 24, 2010

LiDAR Remote Sensing Methodology

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Watershed Sciences, Inc is contracted to provide LiDAR data throughout the Pacific Northwest for the Oregon Department of Geology and Mineral Industries (DOGAMI). This document summarizes overall methodologies for data acquisition and processing. A data report will be provided for each individual project that includes an overview, statistical accuracy assessment and imagery.

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1. Acquisition

1.1 Airborne Survey – Instrumentation and Methods

The Southwest Washington LiDAR survey utilizes both Leica ALS50 Phase II and Leica ALS60 systems mounted in specialized survey aircraft. The systems are set to acquire ≥105,000 laser pulses per second (i.e., 105 kHz pulse rate) at 2000 meters above ground level (AGL), capturing a scan angle of $\pm 24^{o}$ from nadir[1] (i.e., maximum field of view is 48^{o}). These settings are developed to yield points with an average native pulse density (number of pulses emitted by the LiDAR system) of ≥8 points per square meter over terrestrial surfaces. Some (i.e., dense vegetation, water) may return fewer pulses than originally emitted by the laser. Therefore, the overall density may be less than the native density and vary according to distribution of terrestrial features and water bodies.

The survey aircraft provide a powerful, stable platform ideal for the remote and mountainous terrain found in the Pacific Northwest.

All completed areas are surveyed with opposing flight line side-lap of ≥50% (≥100% overlap) to reduce laser shadowing and increase laser painting of angled surfaces. The system allows up to four range measurements per pulse. All discernable laser returns are processed and provided in the output dataset.

To solve for laser point position, it is vital to have an accurate description of aircraft location and attitude/position. Aircraft location 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).

Survey specifications are provided in **Table 2.1**.

A Leica sensor head and operating equipment installed in the aircraft.

[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 as “degrees from nadir”.

Table 2.1 *LiDAR Survey Specifications*

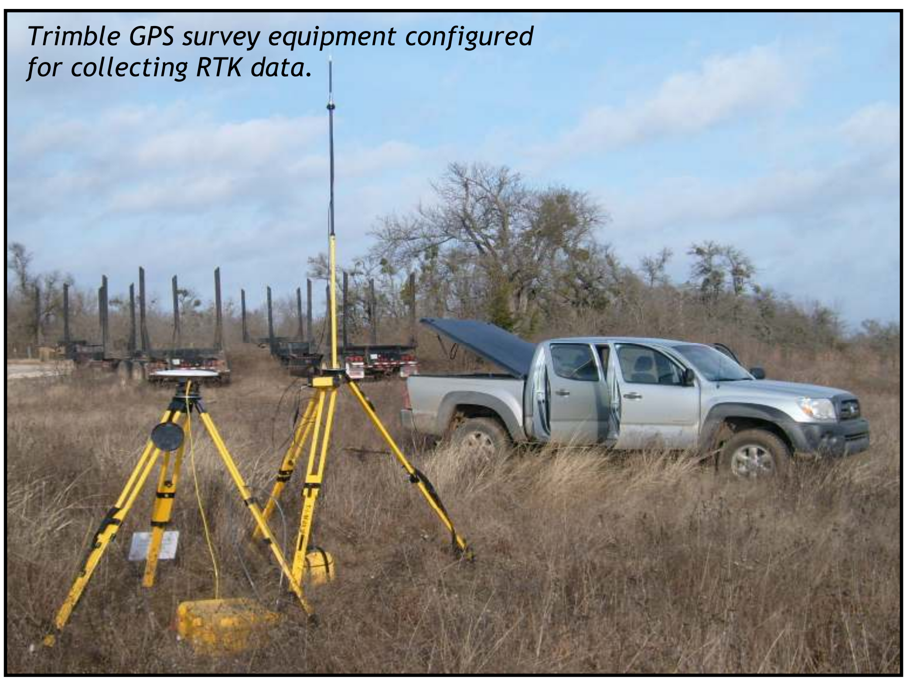
Sensor	Leica ALS50 Phase II, ALS60
Pulse Rate	>105 kHz
Mirror Scan Rate	77Hz, 58Hz
Field of View	48° (±24° from nadir)
Overlap	≥100% (≥50% Side-lap)

1.2 Ground Survey – Instrumentation and Methods

During the LiDAR flight, a static (1 Hz recording frequency) ground survey is conducted over monuments with known coordinates (specific coordinates will be provided in the data report). The static GPS data are post-processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and position accuracy. These static GPS sessions are statistically compared to each other in order to ensure accurate base station coordinates and to eliminate any systematic errors that might otherwise be incorporated into the data. At least three observations with a standard deviation of 1 cm or less are required for a base station location to be used for LiDAR post-processing. In some cases the three session minimum is not possible for real-time kinematic (RTK) base station locations, and instead, a 6-hour session followed by another half-hour session is used for quality control.

1.3 Real-Time Kinematic Survey Results

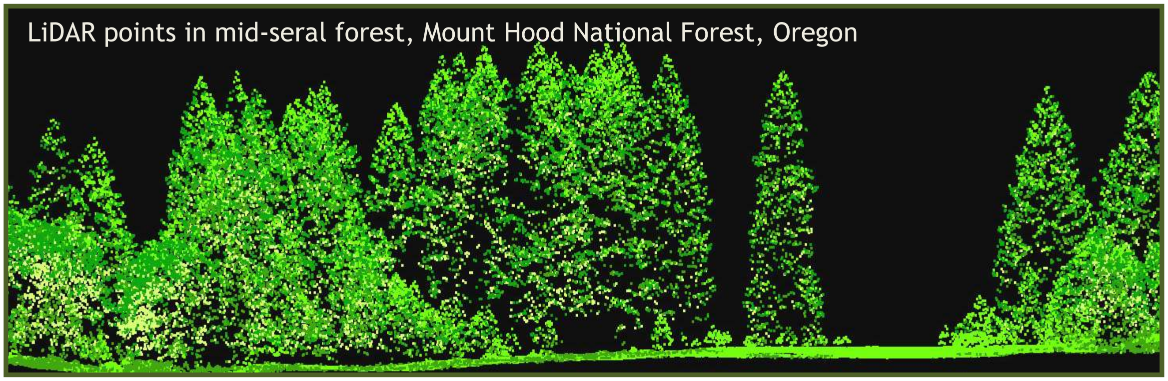
Multiple DGPS units are used for the ground RTK portion of the survey. To collect accurate ground surveyed points, a GPS base unit is set up over a monument to broadcast a kinematic correction to a roving GPS unit. The ground surveyors use a roving unit to receive radio-relayed kinematic corrected positions from the base unit. The RTK survey allows precise location measurement ($\sigma \leq 1.5$ cm ~ 0.6 in). A map of RTK locations are provided in each project report.



Trimble GPS survey equipment configured for collecting RTK data.

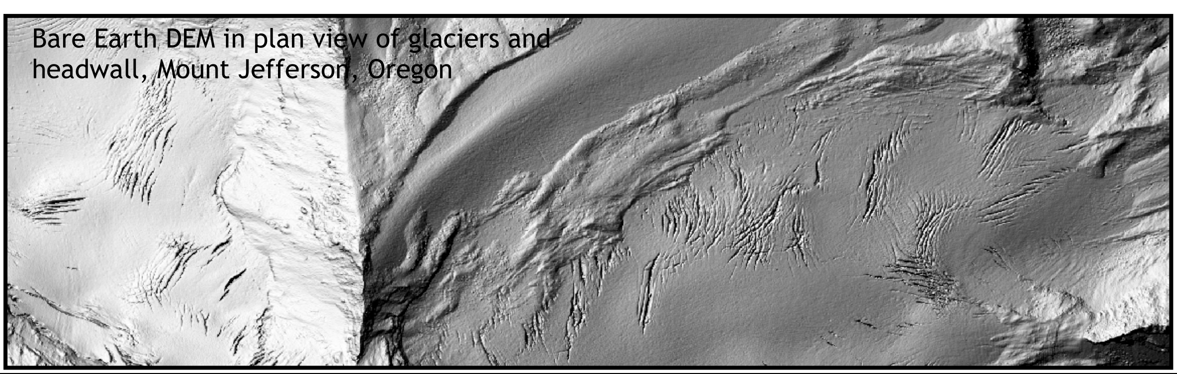
[2] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

2. LiDAR Data Processing


LiDAR points in mid-seral forest, Mount Hood National Forest, Oregon

2.1 Applications and Work Flow Overview

1. Post process kinematic corrections for aircraft location using kinematic aircraft GPS and static ground GPS data.
   Software: Waypoint GPS v.8.1, Trimble Geomatics Office v.1.63
2. Develop a smoothed best estimate of trajectory (SBET) file blending the post-processed aircraft location with attitude data. Sensor head location and attitude are calculated for the survey. The SBET data are then used for laser point processing.
   Software: IPAS Pro v.1.3
3. Calculate laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Create raw laser point cloud data for the entire survey in *.las (ASPRS v1.2) 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, Custom Watershed Sciences software
5. Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are completed 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.
   Software: TerraMatch v.9.001, Custom Watershed Sciences software
6. 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.
   Software: TerraScan v.9.001, ArcMap v9.3, TerraModeler v.9.001, Custom Watershed Sciences software


Bare Earth DEM in plan view of glaciers and headwall, Mount Jefferson, Oregon

2.2 Aircraft Kinematic GPS and IMU Data

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.8.1 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 location. IPAS Pro v.1.3 is used to develop a trajectory file including corrected aircraft location and attitude information. The post-processed trajectory data for the entire flight survey session are incorporated into a final smoothed best estimated trajectory (SBET) file and Terrascan trajectory files.


Pilot and Cessna Caravan with Mt. Hood in background

2.3 Laser Point Processing

Laser point coordinates are computed using the 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) coordinates along with unique intensity values (0-255). The data are output into LAS v. 1.2 files. Each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

To facilitate laser point processing, tiles (polygons) are created to divide large, initial laser point files into manageable sizes (< 500 MB). Point data calibration is performed to correct system offsets for pitch, roll, heading, and mirror scale (structural flex in the mirror mount material). Points from overlapping lines are tested for internal consistency and final adjustments are made for system misalignments. 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 that reduces inconsistencies from sensor attitude offsets, mirror scale, and GPS drift using a comprehensive procedure that uses overlapping survey data.

The LiDAR points are then filtered for noise, pits, and birds by automated screening and manual inspection. Spurious points are removed. For a tile containing approximately 7.5-9.0 million points, an average of 50-100 points are typically found to be artificially low or high. Common sources of non-terrestrial returns are clouds, birds, vapor, and haze.

The TerraSolid software suite is designed specifically for classifying near-ground points. The processing sequence begins by removing all points that are not near the ground surface. The ground surface is refined through a statistical surface algorithm with constraints based on geometric relationships between points as well as point attribute filters. The resulting bare earth model is visually inspected using both triangulated irregular network (TIN) surface models and point cloud data. Additional ground point modeling is performed in site-specific areas to improve ground detail. Where ground point classification includes known vegetation (i.e., understory, low/dense shrubs, etc.) these points are manually reclassified as non-grounds.

3. LiDAR Accuracy and Resolution

3.1 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. Laser noise range 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 flowing or standing water surfaces, moving automobiles, etc.

***Table 3.1**. LiDAR accuracy is a combination of several sources of error. These sources of error are cumulative. Biased error sources which 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


LiDAR-derived highest hit DEM, US Highway 35 crossing of White River, Oregon

3.2 Relative Accuracy

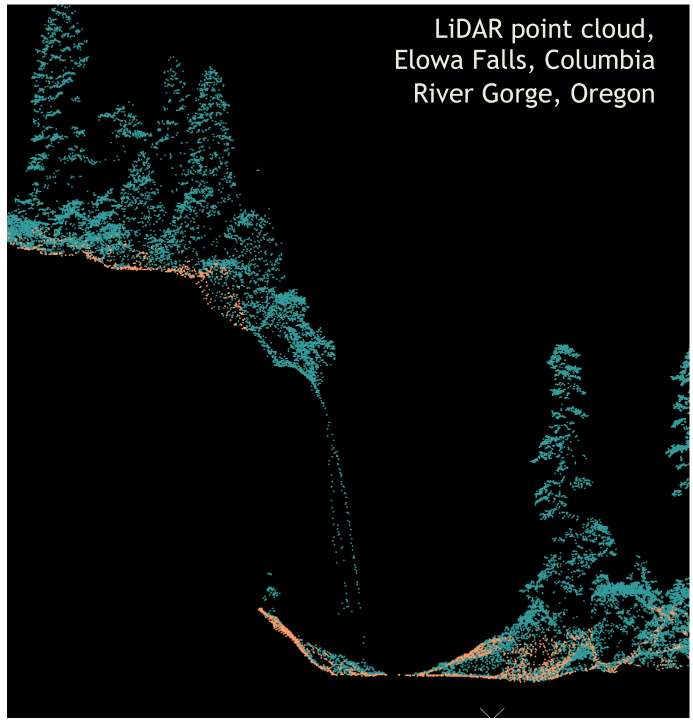
Relative accuracy refers to the internal consistency of the data set, which is measured as the vertical divergence between points from different flight lines occupying the same horizontal location. Vertical divergence is often apparent when flight lines are opposing. When the LiDAR system is well calibrated, the line-to-line divergence is low (<4 cm in certain terrain types). Internal consistency is affected by system attitude offsets (pitch, roll and heading), mirror flex (scale), and GPS/IMU drift. Relative accuracy and statistics, as well as a map of the dates flown for individual flight lines are provided in each project report.

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following is targeted at a flight altitude of 2000 meters above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground. 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 maintained.
3. Reduced Scan Angle: Edge-of-scan data can be inaccurate. Therefore, the scan angle is reduced to a maximum of $\pm 14^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. Quality GPS: Flights are conducted 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 is determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1–second epochs is utilized and a maximum baseline length between the aircraft and the control points is less than 19 km (11.5 miles).
5. Ground Survey: Ground survey point accuracy increases 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. Minimizing laser shadowing helps increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the portion of the flightline closest to nadir coincides with the edge portion (farthest from nadir) of overlapping flight lines. A minimum of 50% side-lap 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 linking 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 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.


LiDAR point cloud, Elowa Falls, Columbia River Gorge, Oregon

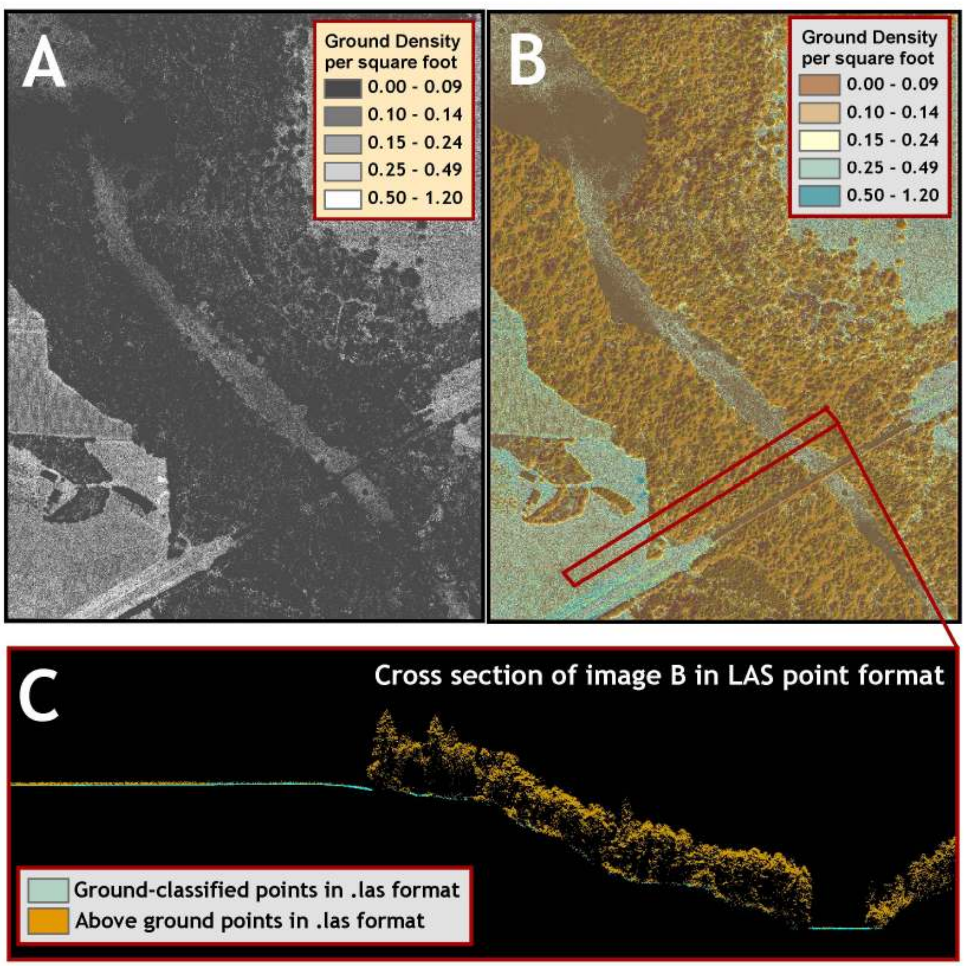
3.3 Absolute Accuracy

The ultimate quality control measure is the statistical accuracy assessment comparing known RTK ground survey points to laser points. Absolute accuracy is typically measured as the standard deviation (sigma, σ) and root mean square error (RMSE). 1-sigma (σ) absolute deviation is defined as the 67^{th} percentile value for the absolute value of the differences between RTK elevations and the modeled LiDAR ground surface. Root Mean Square Error (RMSE) is a statistic used to describe the deviation between true ground surface points (RTK) and the modeled LiDAR surface. As such, the RMSE evaluates the bias of direction and magnitude in the LiDAR data. Absolute accuracy histograms and deviation statistics are provided in each project report.

3.4 Data Density

Data density refers to total LiDAR point resolution (i.e. points per square meter). Pulse density is the number of first return points per area (e.g. square meter). Ground density is the number of ground-classified points (derived from a TIN surface interpolation) per area. Density histograms and maps for both pulse and ground resolution are provided in the data report. Ground density information is conveyed in one of two formats, depending on delivery date. Ground density rasters in .tif format are derived to describe areas of ground resolution based on 3-foot or 1-meter cell spacing (units are relative to delivered datasets). Areas where sampled ground classification point density falls below 0.02 ground classified points per square foot (0.25 points per square meter) are coded as low confidence. Ground density rasters in ESRI DEM format are derived in the following manner: Ground classified point density is sampled for each processing tile with 3-foot or 1-meter resolution. Resulting values represent a true count of ground classified points per sample step (i.e. they are not averaged or interpolated values). Ground classified point density is output as ascii text and converted to ESRI raster format. Low ground resolution may correspond to areas where there is insufficient information to adequately describe near-ground surfaces such as areas with dense vegetation or water surfaces (see **Figure 3.1** below).

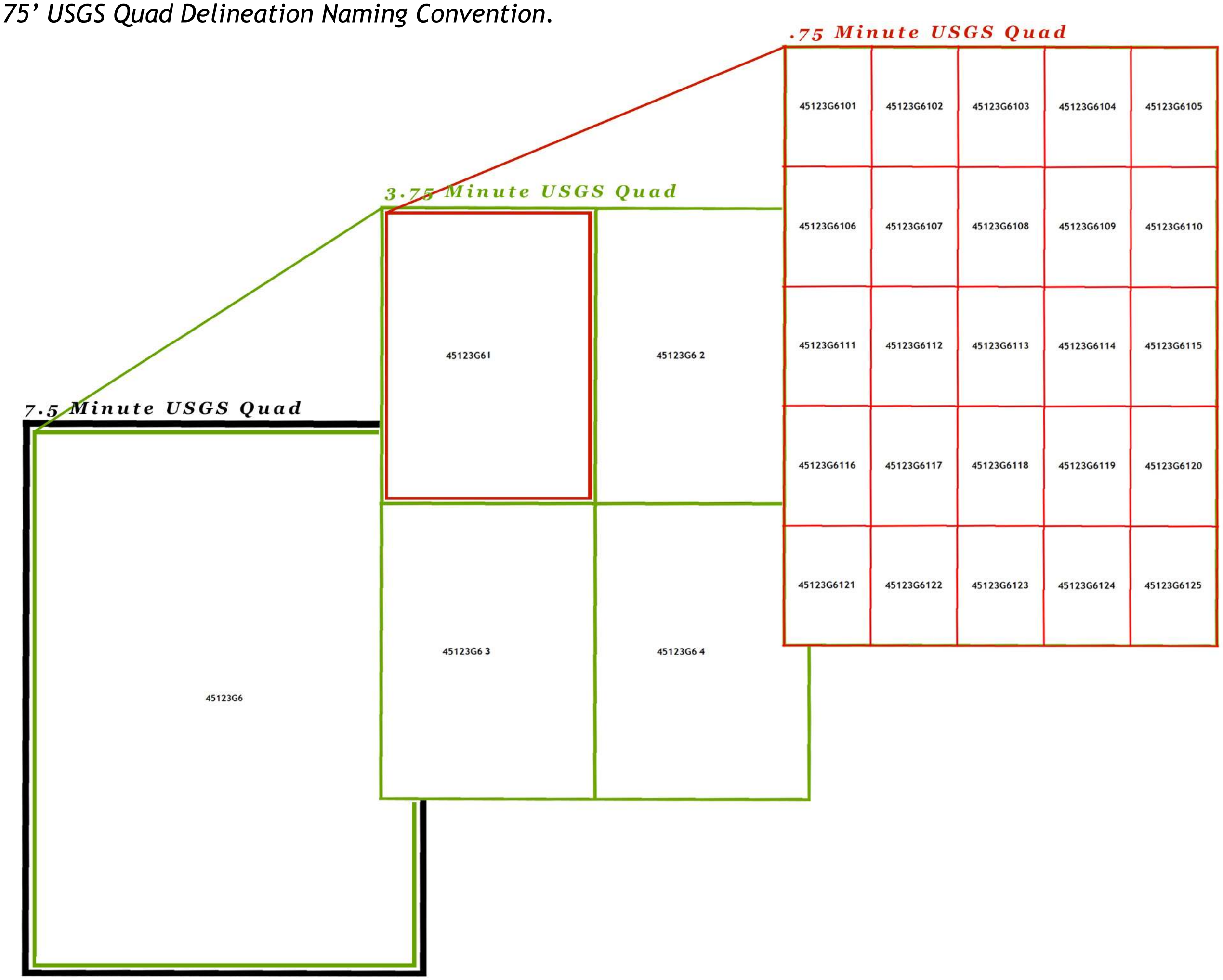
Figure 3.1. ***A:*** Geometric classification of ground density data in ESRI GRID format. ***B:*** Ground density image draped over a highest hit elevation model, demonstrating lower ground-classified point density in areas of thick vegetation and water. ***C:*** Cross section of image '***B***' in point format showing areas of exposed ground, dense vegetation, and water.



4. Deliverables

Bare earth and highest hit ESRI grids of Southwest Washington study area conform to the following tiling scheme (all other data delivered in 750 square meter bin delineation):

Figure 4.1. *0.75' USGS Quad Delineation Naming Convention.*



4.1 Point Data

Point data with fields Number, X, Y, Z, Intensity, ReturnNumber, Class, GPSTime, and RGB value are delivered in 750 square meter processing bins.

- All-classes point cloud in LAS v 1.2 format
- Ground-classified point cloud in LAS v 1.2 format

4.2 Vector Data

- Total Area Flown (TAF)
    - 7.5-minute USGS quadrangle delineation in shapefile format
    - 750 square meter bin delineation in shapefile format (See **Figure 4.1** for illustration)
    - Real Time Kinematic (RTK) survey points in shapefile format

4.3 Raster Data

- ESRI GRID of bare earth modeled LiDAR data points (1-meter resolution) delivered in 7.5' USGS quadrangle delineation
- ESRI GRID of above ground modeled LiDAR data points (1-meter resolution) delivered in 7.5' USGS quadrangle delineation
- Intensity images in GeoTIFF format (.5-meter resolution) delivered per 750 square meter bin delineation
- Ground density rasters in ESRI GRID format (1-meter resolution) delivered per 750 square meter bin delineation

4.4 Data Report

- Full data report containing an introduction, results, and selected imagery.
    - Word format (*.doc)
    - PDF format (*.pdf)

4.5 Datum and Projection

Processing and delivery for these data occurs in: Projection: Universal Transverse Mercator (UTM) Zone 10; horizontal and vertical datum: NAD83 (CORS96)/NAVD88(Geoid03); Units: meters. (Initial ellipsoidal elevations are converted to orthometric elevations according to the published NGS geoid model using ALS software tools.)

5. Glossary

1-sigma (σ) Absolute Deviation: Value representing the 67th percentile of a given data population. Synonymous with 1 standard deviation for a normally distributed dataset.

2-sigma (σ) Absolute Deviation: Value representing the 95th percentile of a given data population. Synonymous with 2 standard deviations for a normally distributed dataset.

Data Density: A measure of LiDAR resolution, measured as points per unit of area.

DEM (Digital Elevation Model): Surface model in raster format. LiDAR DEMs represent modeled ground elevations (bare earth DEM) that are solely derived from triangulated irregular networks (TIN) surfaces. Highest hit rasters are surface models that are calculated as the highest return over a defined area (i.e., every square meter, three square feet, etc.). These surfaces consider the entire dataset including building, vegetation, and ground points.

Intensity: Value corresponding to the power of the laser return. Intensity is a function primarily of pulse emission power, surface reflectivity, and sensor system gain.

Nadir: The perpendicular vector to the ground, directly below the sensor where the scan angle is 0°.

Pulse Return: Return signals captured by the sensor and identified in post processing. The Leica system can record up to four returns in the wave form per laser return. 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.

Overlap: Laser swath area on surveyed surface shared between flight lines, measured as a percentage.

Real-Time Kinematic (RTK) Survey: GPS survey in which both the base station and rover receive differential GPS data. The baseline correction is solved between the two while the survey is in progress.

Root Mean Square Error (RMSE): A measure of error between predicted and observed values derived from modeled systems. RMSE is used to describe the deviation between true ground surface points (RTK) and the modeled LiDAR surface. RMSE provides an estimation of accuracy that includes an evaluation of bias (direction and magnitude) in the LiDAR data.

Scan Angle: The angle from nadir to the edge of scan, measured in degrees.

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