# LiDAR Remote Sensing Data Collection:
# Wenas Valley, WA

## Delivery 2

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Watershed Sciences

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## Delivery 2

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# 1. Overview

Watershed Sciences, Inc. (WS) initially collected 37,969 acres of Light Detection and Ranging (LiDAR) data of the Wenas Valley area of interest (AOI) in Kittitas and Yakima Counties, WA on October 28th, 2009. This data was delivered on November 21st, 2009. After the AOI was clear of snow, the remaining 110,255 acres were collected on March 22nd and from June 12th to June 16th, 2010. The total deliverable area including a 100m buffer is 148,224 acres (**Figure 1**).

*Figure 1*. *Wenas Valley study area*
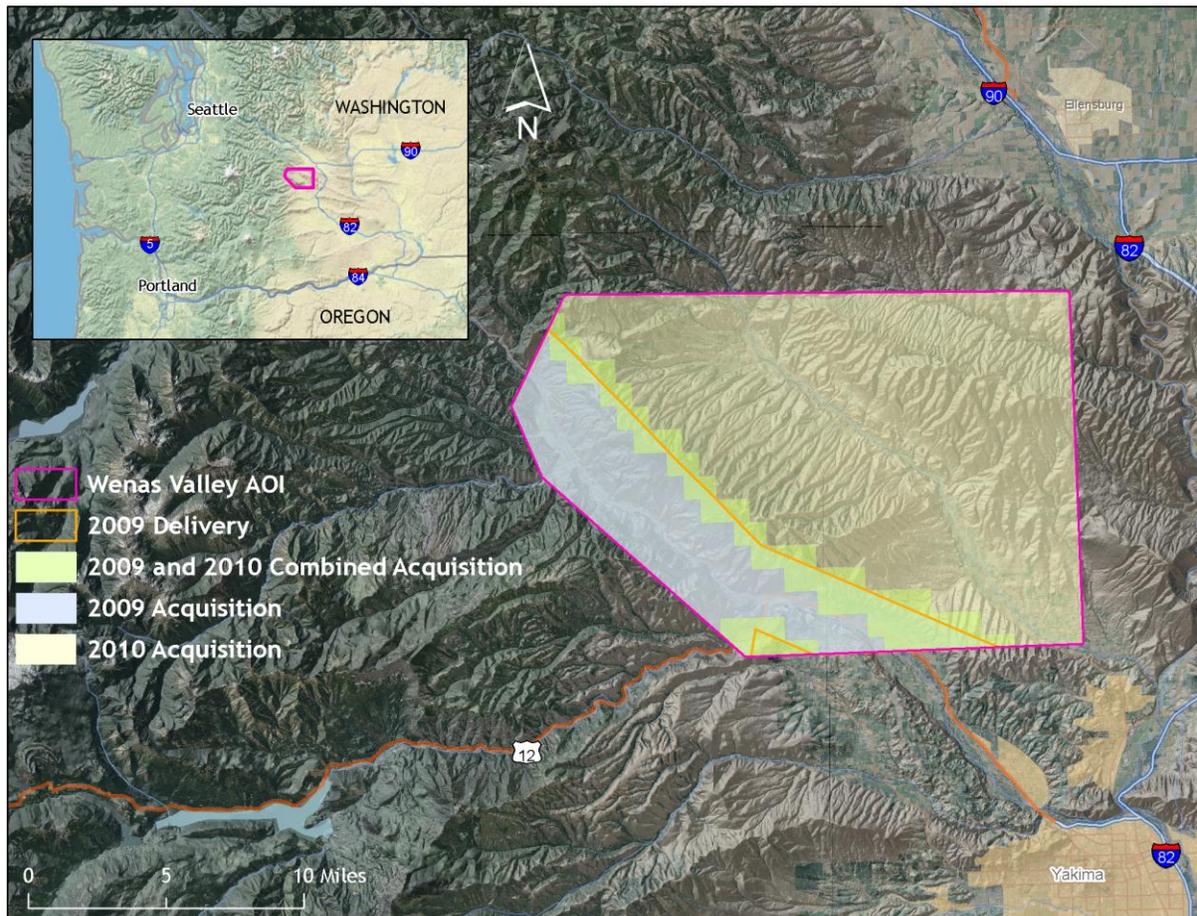
# 2. Acquisition

## 2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey used both the Leica ALS50 Phase II and ALS60 laser systems.  For the Wenas Valley survey, the sensor scan angle was ±14$^o$ from nadir[1] with a pulse rate designed to yield an average native density (number of pulses emitted by the laser system) of $\geq$ 8 points per square meter over terrestrial surfaces.  All survey areas were surveyed with an opposing flight line side-lap of ≥60% (≥100% overlap) to reduce laser shadowing and increase surface laser painting.  The Leica ALS50 Phase II and ALS60 laser systems allow up to four range measurements (returns) per pulse, and all discernable laser returns were processed for the output dataset.  It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses than the laser originally emitted.  These discrepancies between 'native' and 'delivered' density will vary depending on terrain, land cover and the prevalence of water bodies.



The Cessna Caravan is a stable platform, ideal for flying slow and low for high density projects.  The Leica ALS50 sensor head installed in the Caravan is shown on the left.

To accurately solve for laser point position (geographic coordinates x, y, z), the positional coordinates of the airborne sensor and the attitude of the aircraft were recorded continuously throughout the LiDAR data collection mission.  Aircraft position was measured twice per second (2 Hz) by an onboard differential GPS unit.  Aircraft attitude was measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU).  To allow for post-processing correction and calibration, aircraft/sensor position and attitude data are indexed by GPS time.

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[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".

## 2.2 Ground Survey – Instrumentation and Methods

The following ground survey data were collected to enable the geo-spatial correction of the aircraft positional coordinate data collected throughout the flight, and to allow for quality assurance checks on final LiDAR data products.

### 2.2.1 Survey Control

Simultaneous with the airborne data collection mission, we conducted multiple static (1 Hz recording frequency) ground surveys over monuments with known coordinates (**Table 1, Figure 2**).  Indexed by time, these GPS data are used to correct the continuous onboard measurements of aircraft position recorded throughout the mission.  Multiple sessions were processed over the same monument to confirm antenna height measurements and reported position accuracy.  After the airborne survey, these static GPS data were then processed using triangulation with Continuously Operating Reference Stations (CORS) stations, and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance.  Controls were located within 13 nautical miles of the mission area(s).


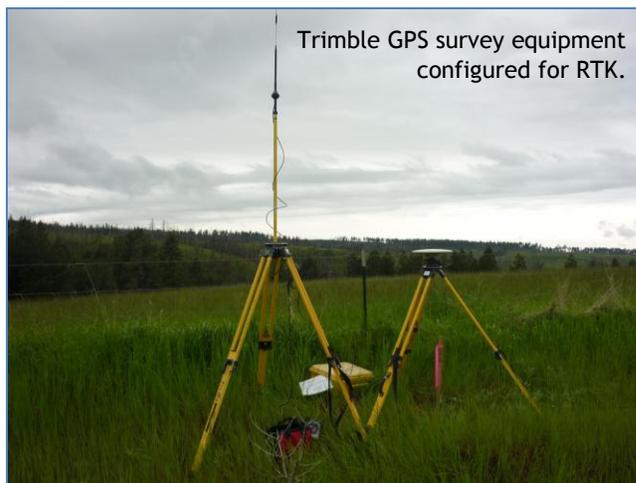Trimble GPS survey equipment configured for RTK.

*Table 1.  Base Station Survey Coordinates, (NAD83/NAVD88, OPUS corrected) used for kinematic post-processing of the aircraft GPS data for delivery 2 of the* Wenas Valley survey area.

| Base Station ID | Datum:   NAD83 (CORS96) | | GRS80 |
|---|---|---|---|
| | Latitude | Longitude | Ellipsoid Z (feet) |
| W_DB3 | 46° 51' 54.21828" | 120° 45' 47.23792" | 2204.241 |
| W_RI1 | 46° 49' 47.74948" | 120° 42' 06.86786" | 1890.049 |
| WSDOT_SKR | 46° 48' 51.41315" | 120° 54' 34.27409" | 2930.476 |
| W_DB1 | 46° 48' 48.18315" | 120° 53' 32.00805" | 3322.346 |

### 2.2.2 RTK Survey

To enable assessment of LiDAR data accuracy, ground check points were collected using GPS based real-time kinematic (RTK) surveying.  For an RTK survey, the ground crew uses a roving unit to receive radio-relayed corrected positional coordinates for all ground points from a GPS base station set up over a survey control monument.  Instrumentation includes multiple

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

Trimble DGPS units (R8). RTK surveying allows for precise location measurements with an error ($\sigma$) of $\leq$ 1.5 cm (0.6 in).

For the RTK survey, the ground crew used a roving unit to receive radio-relayed corrected positional coordinates for all ground truth points from a GPS base station set up over certified survey control monuments. **Figure 2**, below, portrays the distribution of RTK points and base station locations used for the current delivery of Wenas Valley survey area. RTK points were collected on hard surfaces that were easily distinguishable within the LiDAR dataset. Paved surfaces, including roads, paths, and parking lots, were the primary surface target. After all paved surfaces had been exhausted, hard packed gravel roads became the secondary target for RTK, followed by hard packed dirt roads. Hard surfaces are targeted in areas that are clearly visible (and likely to remain visible) from the sky during data acquisition.

In order to facilitate comparisons with LiDAR data, RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads. RTK points were taken no closer than one meter to any nearby terrain breaks such as road edges or drop offs to ensure an accurate comparison between RTK and LiDAR ground data. In addition, attempts were made to collect RTK points on locations that could be readily identified and occupied during subsequent field visits. RTK measurements were collected approximately 1-2 meters from one another to support measurement independence.

An RTK point acquisition period is five seconds long and includes three individual one-second measurements averaged together. The five second observation period ensures that an accurate RTK point was taken. RTK points were not taken during periods when PDOP was greater than three, when less than six satellites were visible, or when horizontal and vertical RMS values were greater than 0.03 m. An RMS value of 0.03 m indicates that an RTK measurement is within 0.03 m of its actual position 68% of the time. An RTK check point was also taken at the beginning and end of each RTK session as close to the base station location as possible to provide an on-the-spot vertical accuracy check.

**Figure 2.** *RTK and base station locations used for the Wenas Valley study area.*
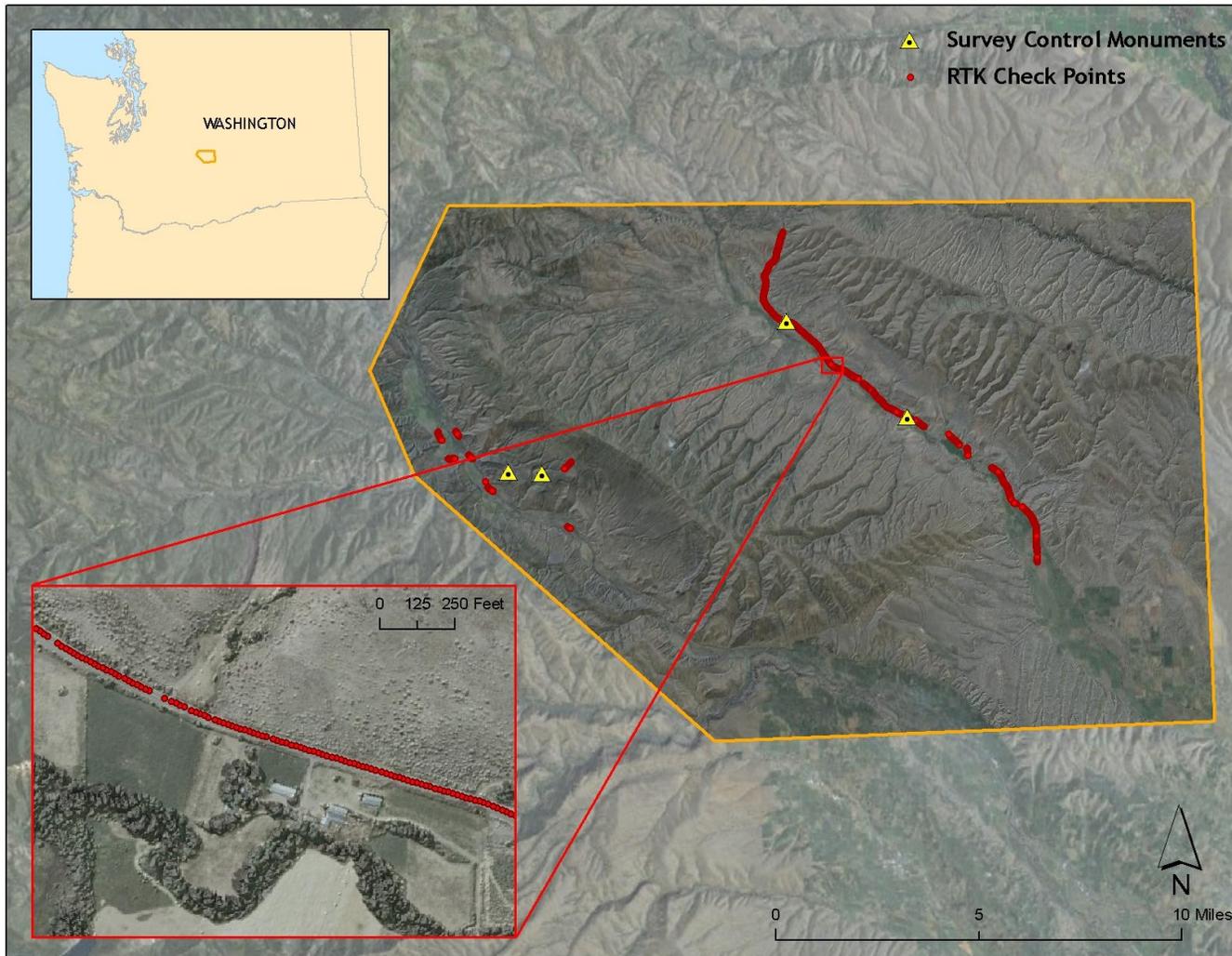
# 3. Data Processing

## 3.1 Applications and Work Flow Overview

1. Resolved 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. Developed a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with attitude data Sensor head position and attitude were calculated throughout the survey. The SBET data were used extensively for laser point processing.
   **Software:** IPAS v.1.35
3. Calculated laser point position by associating SBET position to each laser point return time, scan angle, intensity, etc. Created raw laser point cloud data for the entire survey in *.las (ASPRS v1.2) format.
   **Software:** ALS Post Processing Software v.2.7
4. Imported raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points were then classified for individual flight lines (to be used for relative accuracy testing and calibration).
   **Software:** TerraScan v.9.001 (2009) and v. 10.009 (2010)
5. Using ground classified points per each flight line, the relative accuracy was tested. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations were performed on ground classified points from paired flight lines. Every flight line was used for relative accuracy calibration.
   **Software:** TerraMatch v.10.006
6. Position and attitude data were imported. Resulting data were classified as ground and non-ground points. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data. Data were then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction. Ground models were created as a triangulated surface and exported as ArcInfo ASCII grids at a 3-foot pixel resolution.
   **Software:** TerraScan v.10.009, ArcMap v.9.3, TerraModeler v.10.004

## 3.2 Aircraft Kinematic GPS and IMU Data

LiDAR survey datasets were referenced to the 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collected 2 Hz kinematic GPS data, and the onboard inertial measurement unit (IMU) collected 200 Hz aircraft attitude data. Leica IPAS Suite was used to process the kinematic corrections for the aircraft. The static and kinematic GPS data were then post-processed after the survey to obtain an accurate GPS solution and aircraft positions. Waypoint was used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session were 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 were 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) were assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data were output into large 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.

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

Laser point data were imported into processing bins in TerraScan, and manual calibration was performed to assess the system offsets for pitch, roll, heading and scale (mirror flex). Using a geometric relationship developed by Watershed Sciences, each of these offsets was resolved and corrected if necessary.

LiDAR points were filtered for noise, pits (artificial low points) and birds (true birds as well as erroneously high points) by screening for absolute elevation limits, isolated points and height above ground. Each bin was then manually inspected for remaining pits and birds and spurious points were removed. In 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. Common sources of non-terrestrial returns are clouds, birds, vapor, haze, decks, brush piles, etc. Internal calibration was refined using TerraMatch. Points from overlapping lines were tested for internal consistency and final adjustments were made for system misalignments (i.e., pitch, roll, heading offsets and scale). Automated sensor attitude and scale corrections yielded 3-5 cm improvements in the relative accuracy. Once system misalignments were corrected, vertical GPS drift was then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy.

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

Final points were imported into 1/100th USGS quads. Some quads containing points from both 2009 and 2010 were too large for processing (>20,000,000 points) and were broken into 1/400th USGS quads **(Figure 8)**.

# 4. LiDAR Accuracy Assessment

Our LiDAR quality assurance process uses the data from the real-time kinematic (RTK) ground survey conducted in the survey area.  In this project, a total of 3120 RTK GPS measurements were collected on hard surfaces distributed among multiple flight swaths.  To assess absolute accuracy, we compared the location coordinates of these known RTK ground survey points to those calculated for the closest laser points.

## 4.1 Laser Noise and Relative Accuracy

Laser point absolute accuracy is largely a function of laser noise and relative accuracy.  To minimize these contributions to absolute error, we first performed a number of noise filtering and calibration procedures prior to evaluating absolute accuracy.

*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 survey was approximately 0.02 meters.

*Relative Accuracy*
Relative accuracy refers to the internal consistency of the data set - the ability to place a laser point in the same location over multiple flight lines, GPS conditions, and aircraft attitudes.  Affected by system attitude offsets, scale, and GPS/IMU drift, internal consistency 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).  See Appendix A for further information on sources of error and operational measures that can be taken to improve relative accuracy.

*Relative Accuracy Calibration Methodology*
1. <u>Manual System Calibration</u>:  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 were calculated and applied to resolve misalignments.  The raw divergence between lines was computed after the manual calibration was completed and reported for each survey area.
2. <u>Automated Attitude Calibration</u>:  All data were tested and calibrated using TerraMatch automated sampling routines.  Ground points were classified for each individual flight line and used for line-to-line testing.  System misalignment offsets (pitch, roll and heading) and scale were solved for each individual mission and applied to respective mission datasets.  The data from each mission were then blended when imported together to form the entire area of interest.
3. <u>Automated Z Calibration</u>:  Ground points per line were utilized to calculate the vertical divergence between lines caused by vertical GPS drift.  Automated Z calibration was the final step employed for relative accuracy calibration.

## 4.2 Absolute Accuracy

The vertical accuracy of the LiDAR data is described as the mean and standard deviation (sigma ~ $\sigma$) of divergence of LiDAR point coordinates from RTK ground survey point coordinates.  To provide a sense of the model predictive power of the dataset, the root mean square error (RMSE) for vertical accuracy is also provided. These statistics assume the error distributions for x, y, and z are normally distributed, thus we also consider the skew and kurtosis of distributions when evaluating error statistics.

Statements of statistical accuracy apply to fixed terrestrial surfaces only and may not be applied to areas of dense vegetation or steep terrain. To calibrate laser accuracy for the LiDAR dataset, 3120 RTK ground check points were collected on fixed, hard-packed road surfaces within the survey area.

# 5. Study Area Results

Summary statistics for point resolution and accuracy (relative and absolute) of the LiDAR data collected in the Wenas Valley survey area are presented below in terms of central tendency, variation around the mean, and the spatial distribution of the data (for point resolution by 1/100th USGS Quad).

## 5.1 Data Summary

*Table 2*.  *Resolution and Accuracy - Specifications and Achieved Values*

|  | Targeted | Achieved |
|---|---|---|
| Resolution: | $\geq$ 8 points/m$^2$ | 0.78 points/ft$^2$<br>(8.37 points/m$^2$) |
| *Vertical Accuracy (1 $\sigma$): | <15 cm | 0.17 ft<br>(5.19 cm) |

## 5.2 Data Density/Resolution

Certain types of surfaces (e.g., dense vegetation, breaks in terrain, steep slopes, water) may return fewer pulses (delivered density) than the laser originally emitted (native density). The overall resolution (average first-return laser point density) was slightly higher than the targeted density.  Some bins do have lower densities than the targeted resolution, this can happen because of terrain breaks, steep slopes, and even the occurrence of water (**Figure 5**), but flight planning was optimized to collect the targeted data resolution.

Ground classifications were derived from automated ground surface modeling and manual, supervised classifications where it was determined that the automated model had failed. Ground-classified return densities will be lower in areas of dense vegetation, water, or buildings.

**Figures 3**and **4** display the density distribution of average first return and ground classified laser points.  Similarly, **Figure 5** shows the first return and ground classified point densities per USGS quad. Areas of combined 2009 and 2010 data have the highest native point density.

**Data Resolution for the Wenas Valley survey area:**

- o   Average Point (First Return) Density = 0.78 points/ft$^2$ (8.37 points/m$^2$)
- o   Average Ground Point Density = 0.35 points/ft$^2$ (3.75 points/m$^2$)

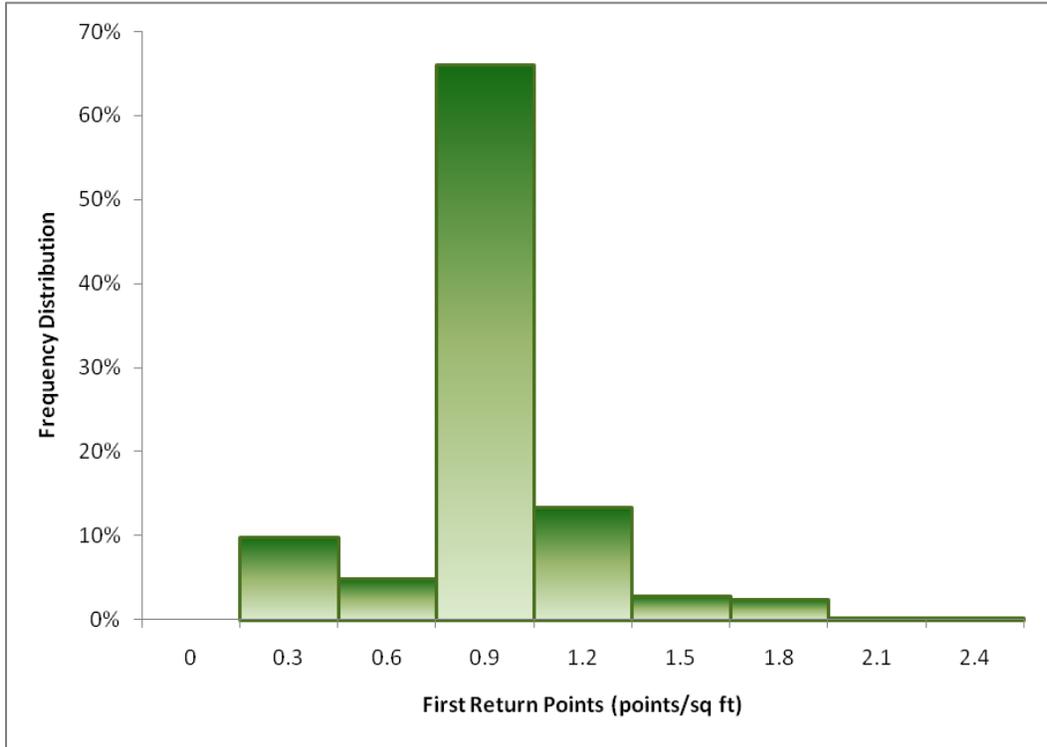*Figure 3.  Density distribution for first return laser points*

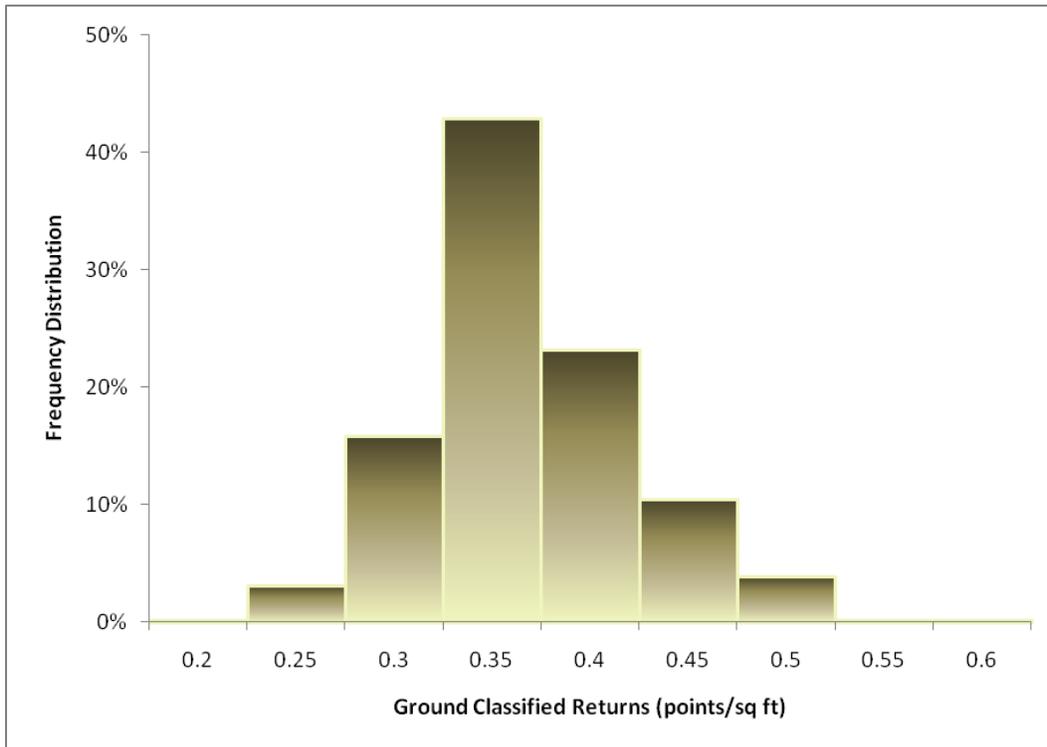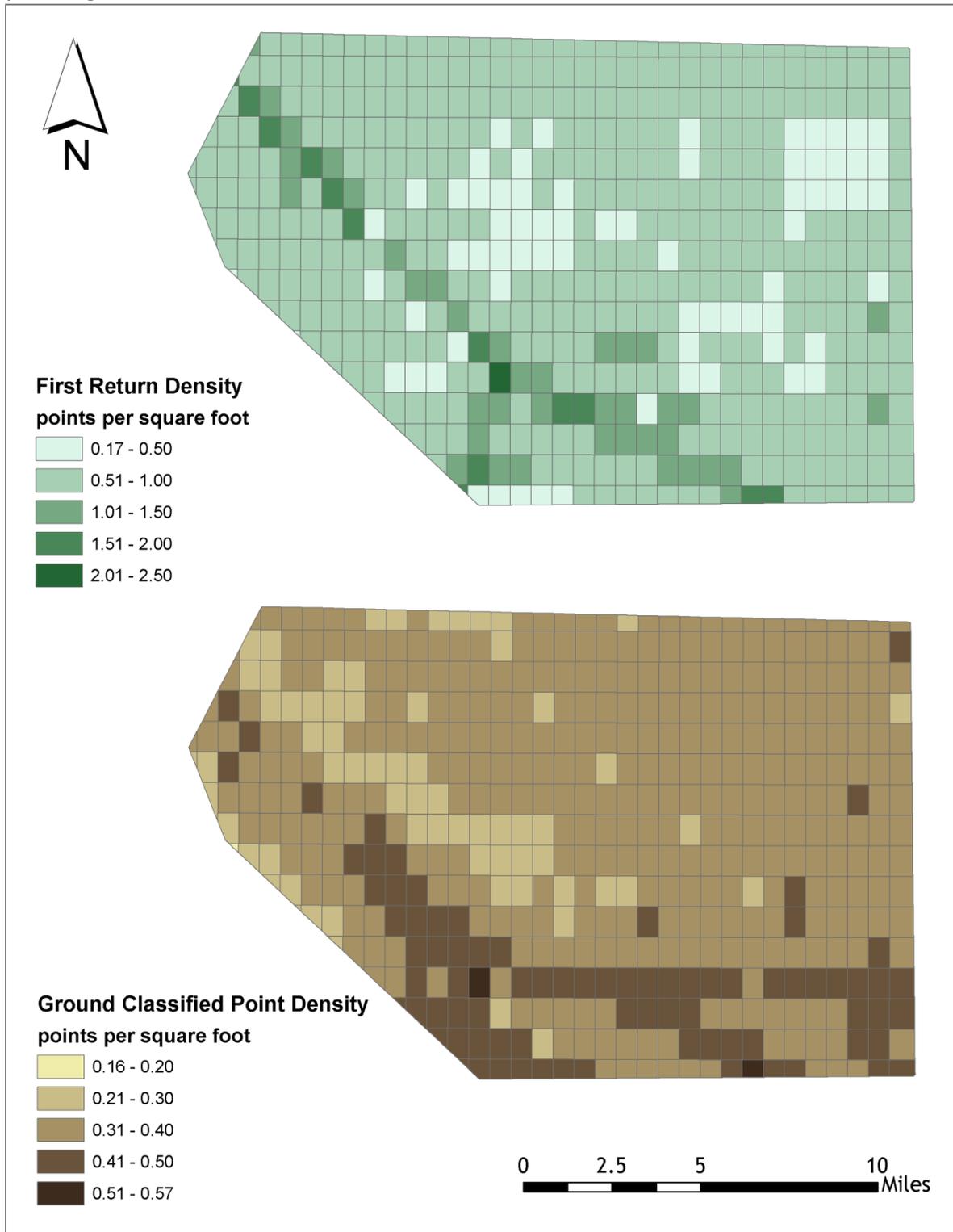*Figure 4*. *Density distribution for ground classified laser points.*

**Figure 5**. *First return and Ground classified laser point data density per USGS 1/100th quadrangle*



First Return Density
points per square foot

- 0.17 - 0.50
- 0.51 - 1.00
- 1.01 - 1.50
- 1.51 - 2.00
- 2.01 - 2.50

Ground Classified Point Density
points per square foot

- 0.16 - 0.20
- 0.21 - 0.30
- 0.31 - 0.40
- 0.41 - 0.50
- 0.51 - 0.57

## 5.3 Relative Accuracy Calibration Results

Relative accuracies for the Wenas Valley survey area:

- o  Project Average = 0.16 ft (4.9 cm)
- o  Median Relative Accuracy = 0.15 ft (4.7 cm)
- o  1$\sigma$ Relative Accuracy = 0.16 ft (5.0 cm)
- o  2$\sigma$ Relative Accuracy = 0.21 ft (6.4 cm)

**Figure 6**. *Distribution of relative accuracies per flight line, non slope-adjusted*
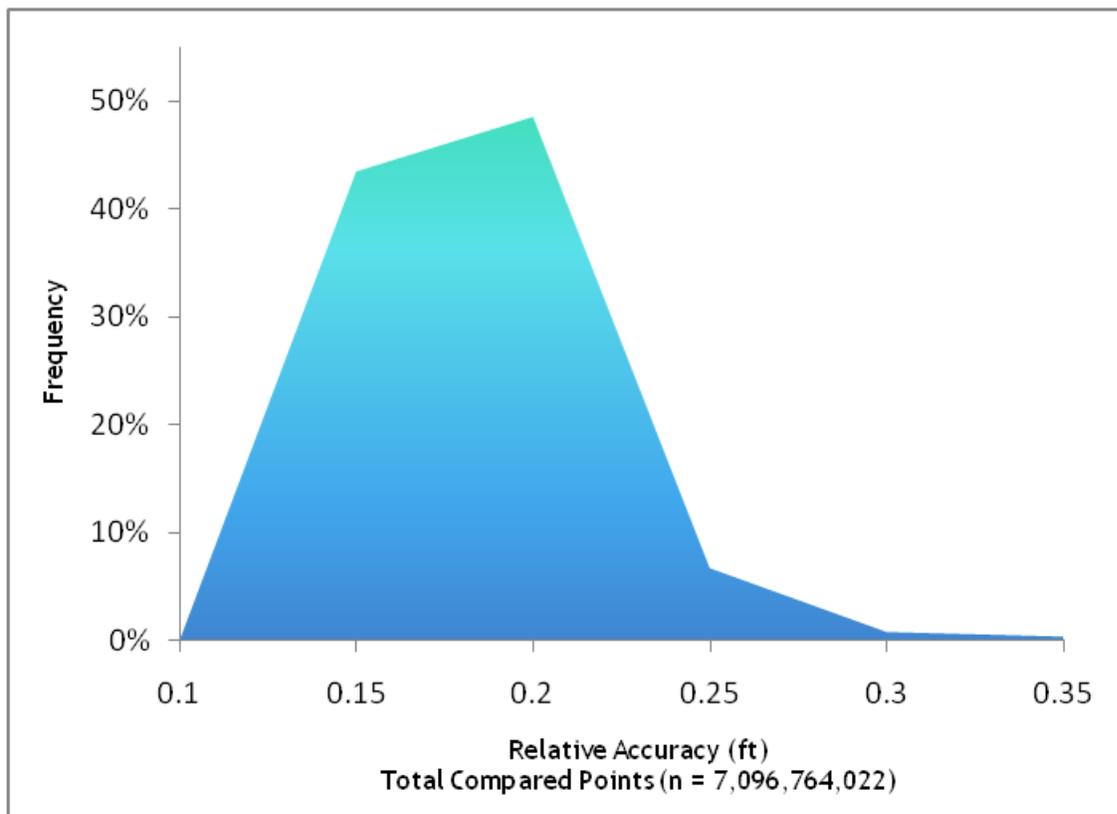
## 5.4 Absolute Accuracy

Absolute accuracies for the Wenas Valley survey area:

*Table 3*.  *Absolute Accuracy – Deviation between laser points and RTK hard surface survey points*

| RTK Survey Sample Size (n): 3120 | | |
|---|---|---|
| Root Mean Square Error (RMSE) =   0.17ft (5.2 cm) | | Minimum Δz = -0.52 ft (-15.8 cm) |
| Standard Deviations: | | Maximum Δz = 0.44 ft (13.3 cm) |
| 1 sigma (σ) = 0.17 ft (5.2 cm) | 2 sigma (σ) = 0.32 ft (8.9 cm) | Average Δz = -0.03 ft (-1.0 cm) |

*Figure 7*.  *Absolute Accuracy - Histogram Statistics, based on 3120 hard surface points*
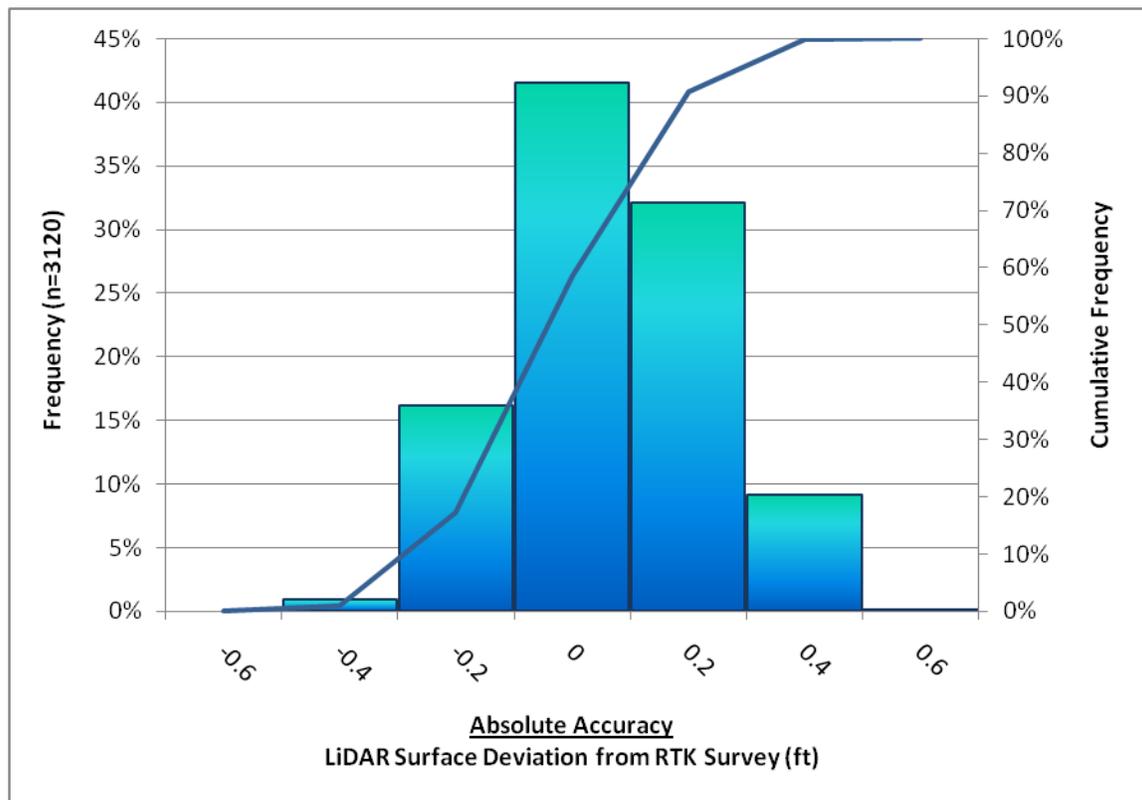
## 5.5 Projection/Datum and Units

| Projection: | | Washington State Plane South FIPS 4602 |
|---|---|---|
| Datum | Vertical: | NAVD88 Geoid03 |
| | Horizontal: | NAD83 (HARN) |
| Units: | | U.S. Survey Feet |

# 6. Deliverables

| Point Data: | • All laser returns (LAS v. 1.2 format; 1/100th USGS quad delineation)<br>• All laser returns (ASCII text format; 1/100th USGS quad delineation)<br>• Ground classified points (ASCII text format; 1/100th USGS quad delineation) |
|---|---|
| Vector Data: | • Delivered Area (shapefile format)<br>• 1/100th USGS quad delineation (shapefile format)<br>• 1/4th USGS quad delineation (shapefile format)<br>• SBET Trajectories (ASCII text format) |
| Raster Data: | • Elevation models (3-ft resolution):<br>  • Bare Earth Model (ESRI GRID format; 1/4th USGS quad delineation)<br>  • Highest Hit Model (ESRI GRID format; 1/4th USGS quad delineation)<br>• Intensity images (GeoTIFF format, 1.5-ft resolution, 1/100th USGS quad delineation) |
| Data Report: | Full report containing introduction, methodology, and accuracy |

Point Data (per 1/100th USGS Quad delineation*)
LAS v1.2 or ASCII Format

*Note: Delineation based on 1/100th of a full 7.5-minute USGS Quad (.075-minutes). Larger delineations, such as 1/64th USGS Quads, resulted in unmanageable file sizes due to high data density. In some cases, even the 1/100th delineation was too large due to the incorporation of data from 2009 and 2010. In these few instances, a 1/400th of a full 7.5-minute USGS Quad (.0375 - minutes) was used for more manageable data.

**Figure 8.** Quadrangle naming convention for 1/100th & /400th of a 7.5-minute USGS Quad.
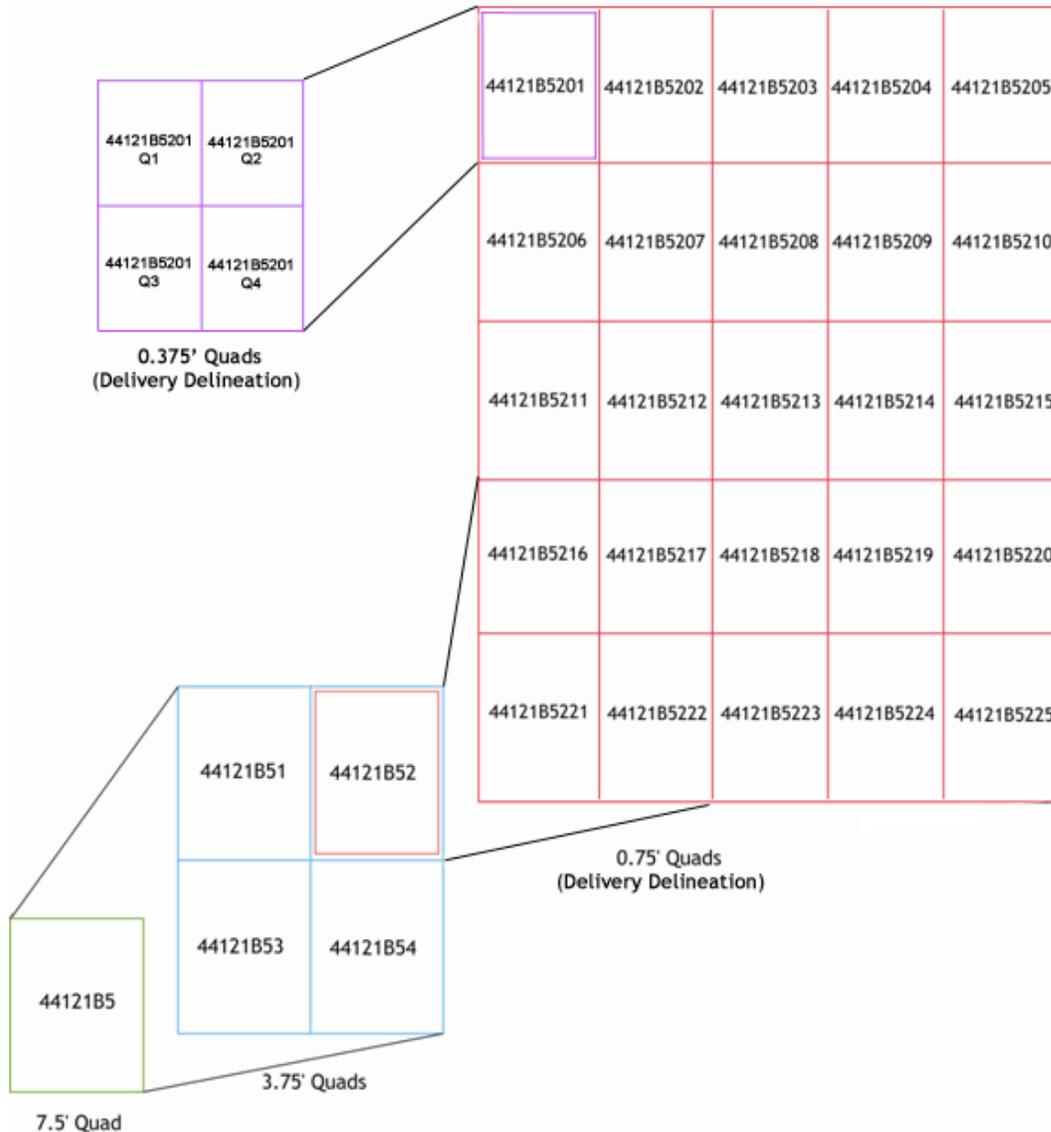
# 7. Selected Images

**Figure 9.** 3D view of landslide area looking North (the top image is derived from ground-classified LiDAR points, the bottom image is derived from highest-hit LiDAR points).
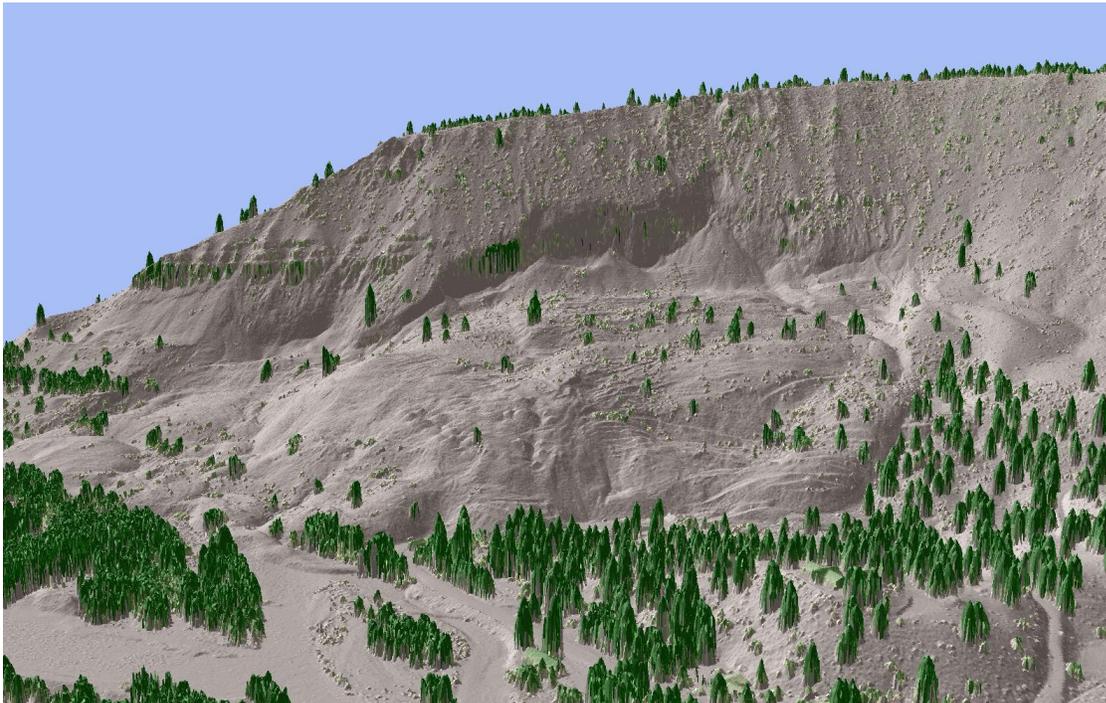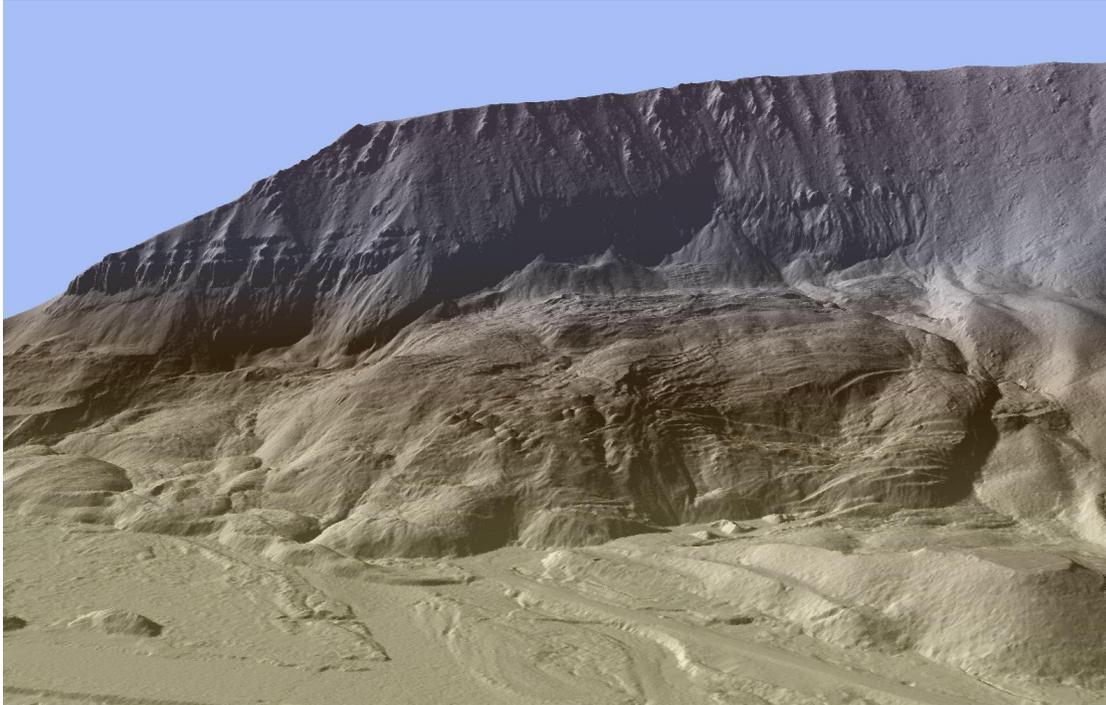
**Figure 10.** Upstream view of the Naches River; the image is a LiDAR derived point cloud colored by elevation textured by intensity.
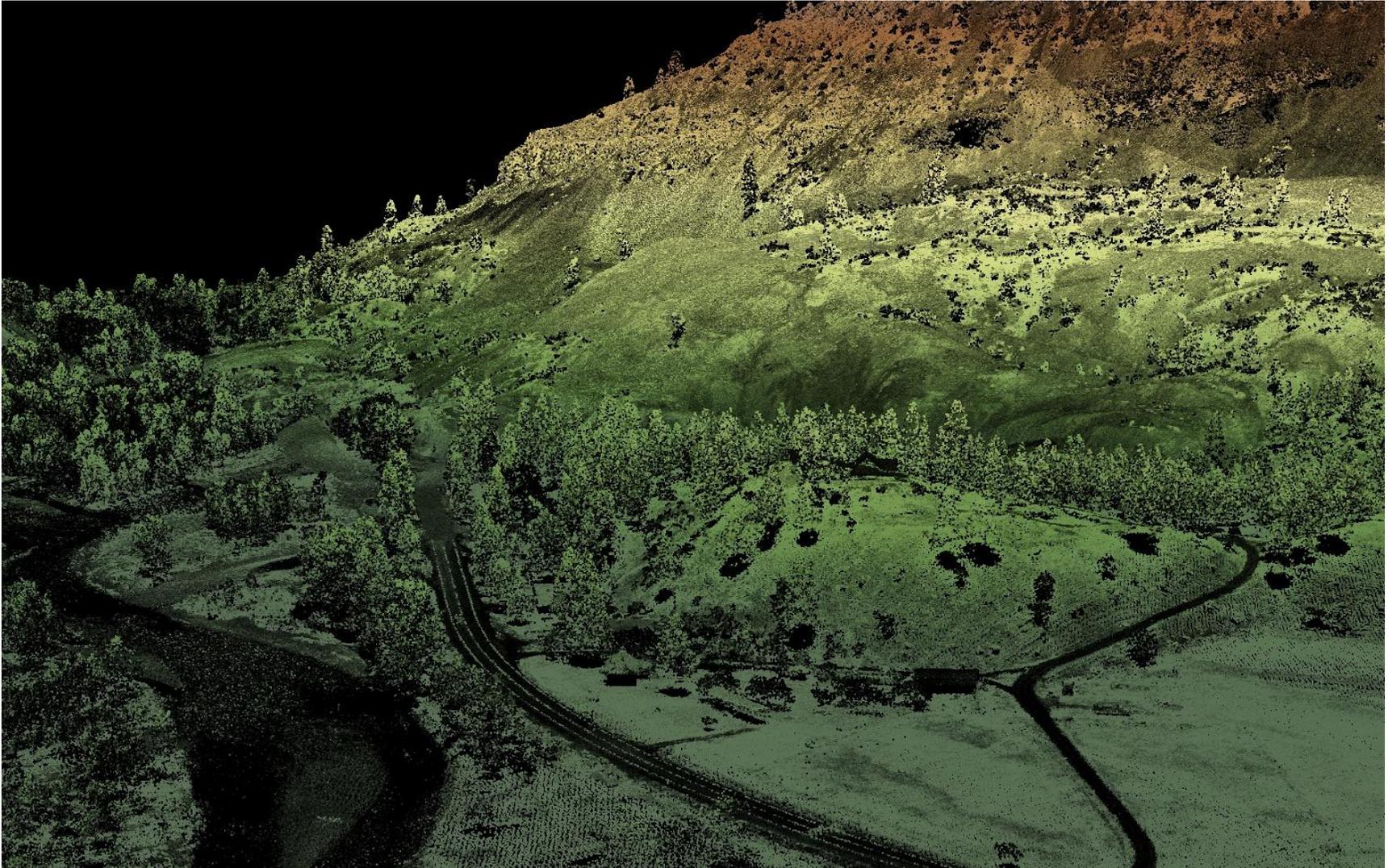
**Figure 11.** 3D point cloud of the confluence of Umtanum Creek and a dry gulch colored by elevation. Image looking upstream at the southwest bank hillside talus aprons that are present due to slope instability.
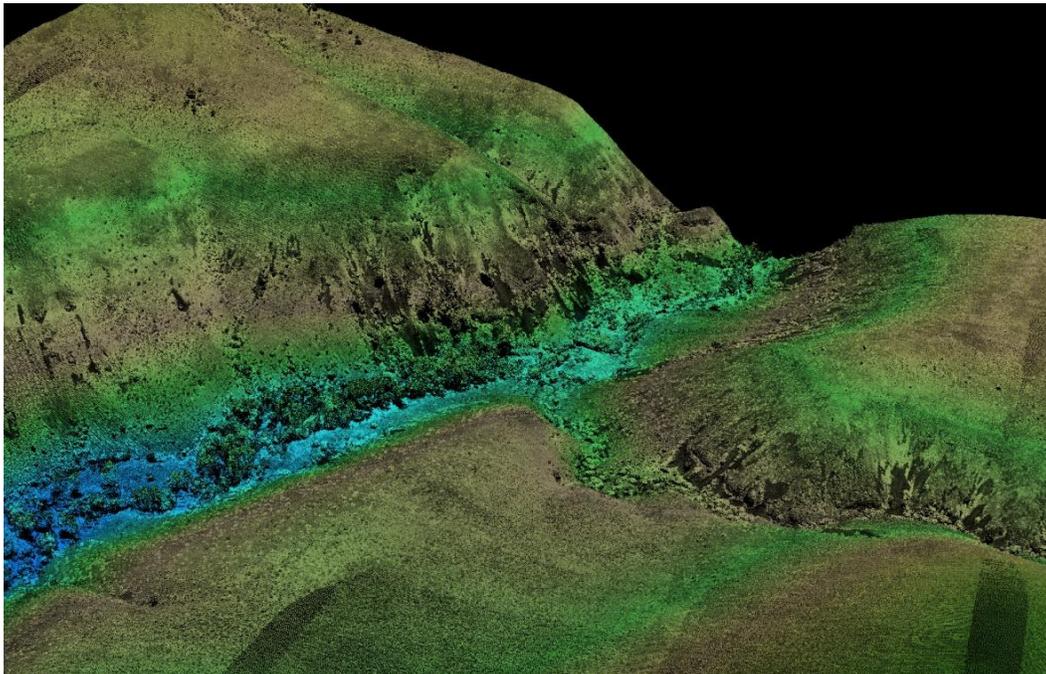


**Figure 12.** 3D point cloud of the Wenas Dam. Image looking northwest across Wenas Lake with N. Wenas Rd. along the right side of image. LiDAR scan pattern is noticeable across the lake as well on the land in foreground and adjacent to the road.
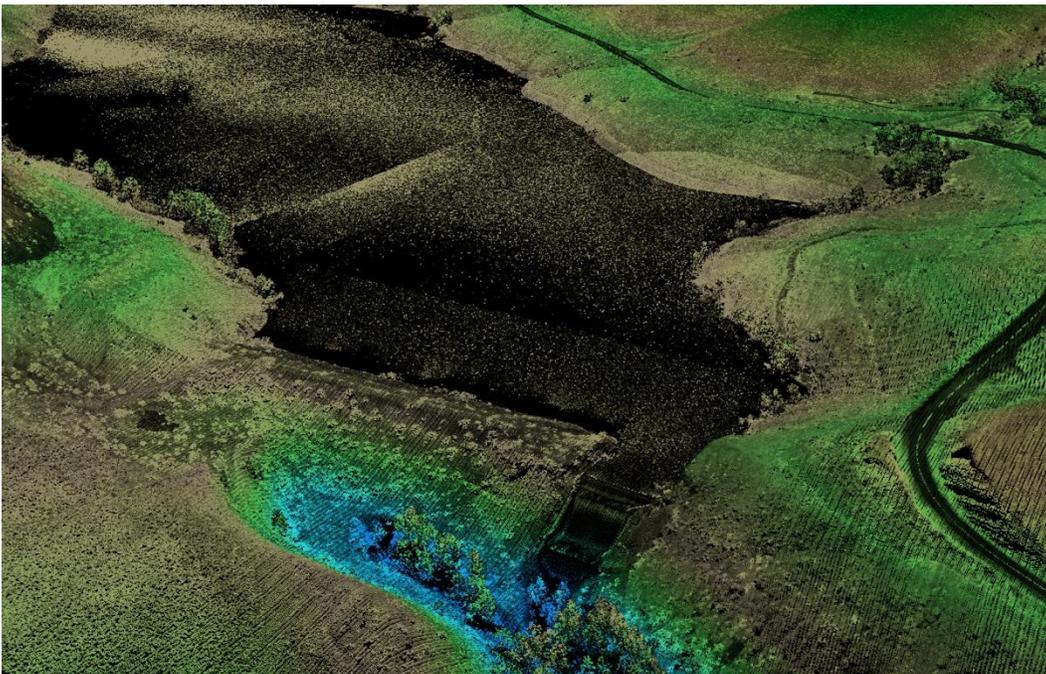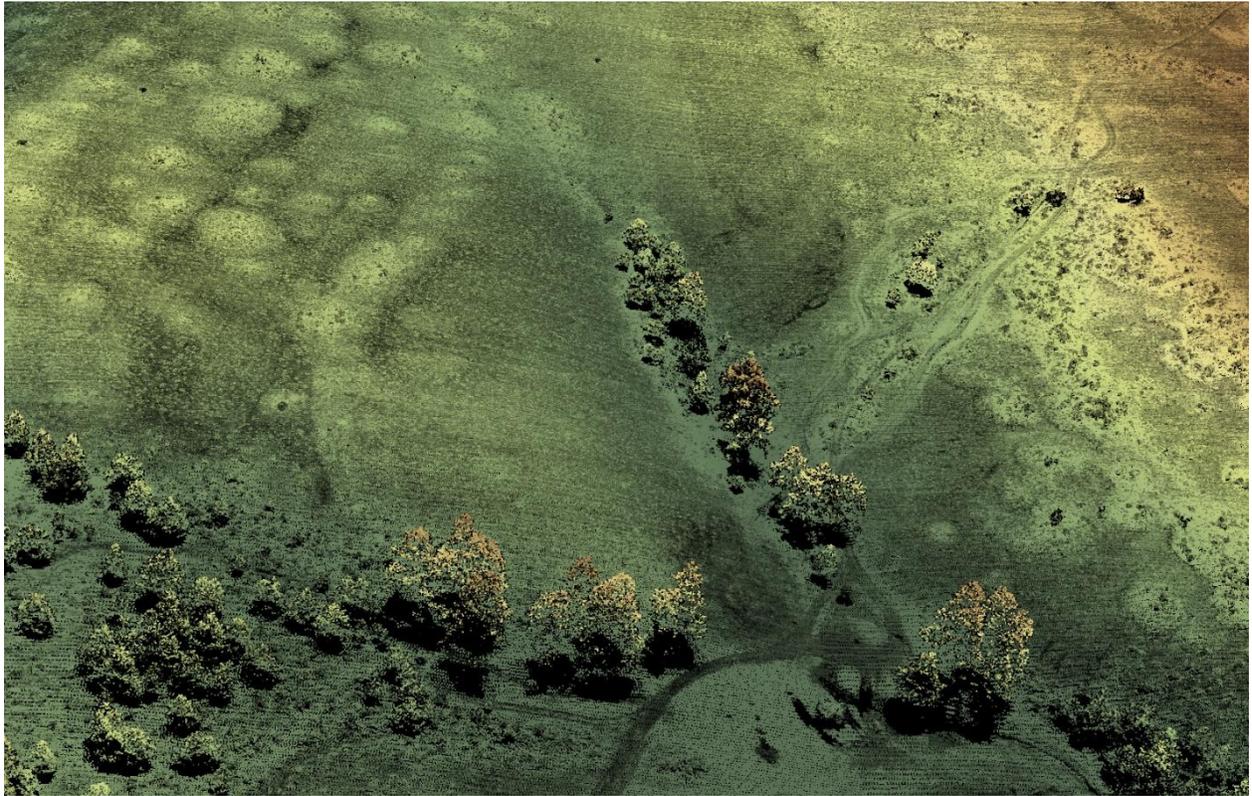
**Figure 13.** 3D point cloud of mima mounds along Umtanum Ridge colored by elevation. Aerial view of the headwaters of Kelley Hollow near Oasis Spring.

# 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.

**1.96-sigma (σ) Absolute Deviation:**  Value for which the data are within two standard deviations (approximately 96th 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 pulse 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, $\sigma$) 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.

# Appendix A

LiDAR accuracy error sources and solutions:

| 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 |

Operational measures taken to improve relative accuracy:

Low Flight Altitude:  Terrain following is employed to maintain a constant above ground level (AGL).  Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 1/3000th AGL flight altitude).

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.

Reduced Scan Angle:  Edge-of-scan data can become inaccurate.  The scan angle was reduced to a maximum of ±14° from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.

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.

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.  Ground survey RTK points are distributed to the extent possible throughout multiple flight lines and across the survey area.

60% 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 60% side-lap, the most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines.  A minimum of 60% side-lap with terrain-followed acquisition prevents data gaps.

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.