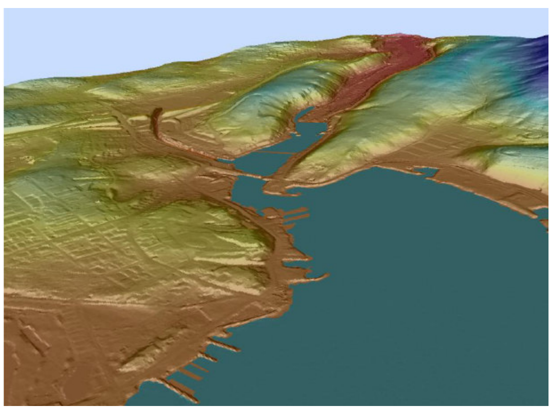
LiDAR Report:

Klamath River LiDAR and Mapping, 2010

Link River Dam, OR to the confluence with Elk Creek south of Happy Camp, CA

US Bureau of Reclamation IDIQ contract 08-CA-40-8258
Task Order: R10PD40007



For:
US Bureau of Reclamation

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LiDAR Remote Sensing Data Collection:
Klamath River, CA/OR

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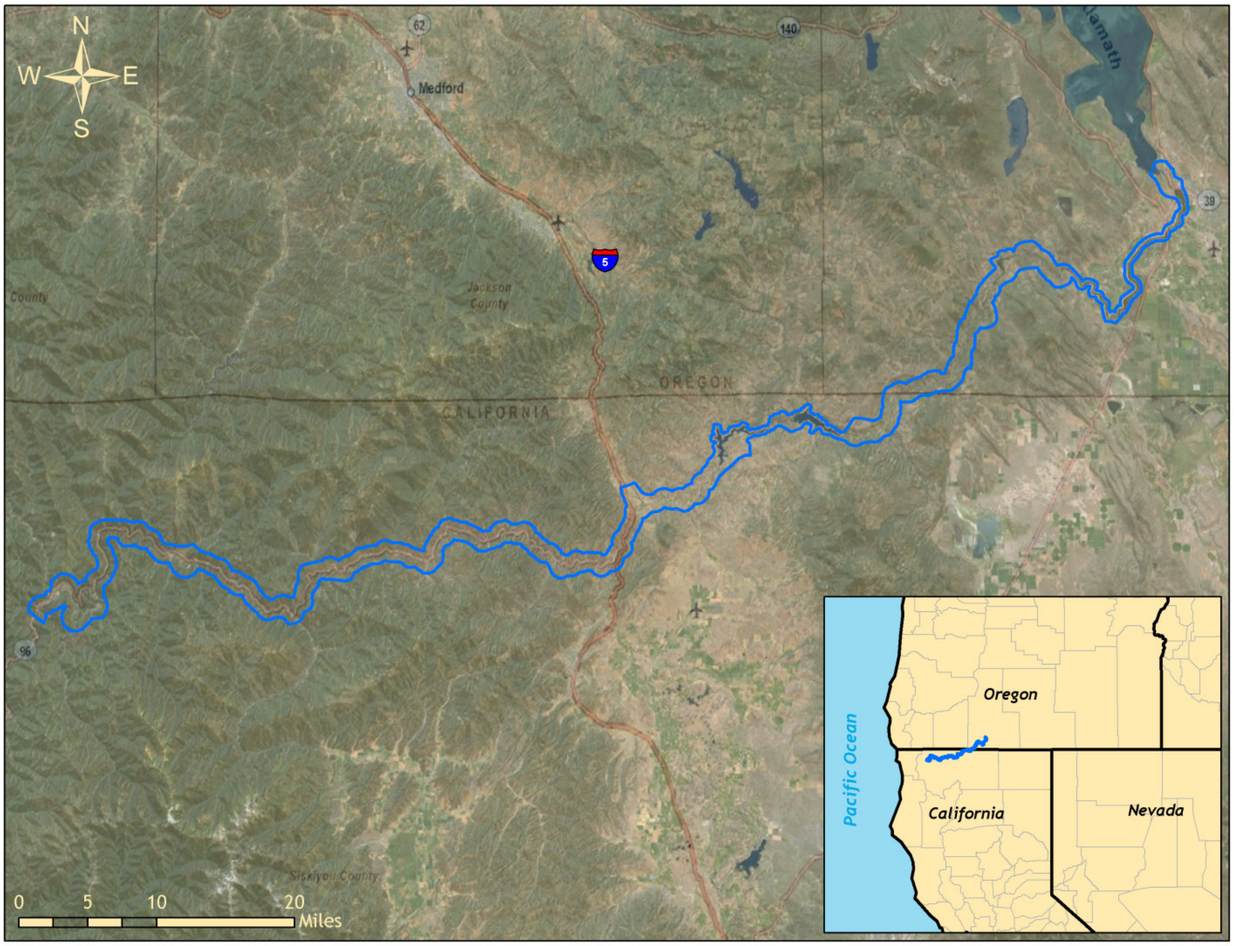
1. Overview

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the Klamath River and associated riparian zones from Klamath Falls, Oregon to Happy Camp, California for Woolpert, Inc. (Contract Number: 08-CA-40-8258; Task Order: 08-XX-40-8258).

Acquisition of the data occurred between February 27th and March 15th, 2010. The total deliverable area, including a 100 m buffer, is 107,547 acres (**Figure 1**).

Figure 1. *Klamath River survey area overview.*



2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey uses a Leica ALS60 laser system. For the Klamath River survey area, the sensor scan angle was $\pm 13^{\circ}$ from nadir[1] with a pulse rate designed to yield an average native density (number of pulses emitted by the laser system) of ≥ 8 points per square meter over terrestrial surfaces. All survey areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap). The Leica ALS60 system allows 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 ALS60 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.

[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

Woolpert, Inc. provided ground survey and control certification (CA PLS) for an extensive survey network within the project area. Simultaneous with the airborne data collection mission, WSI conducted multiple static (1 Hz recording frequency) GPS surveys over selected monuments within this network (**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.

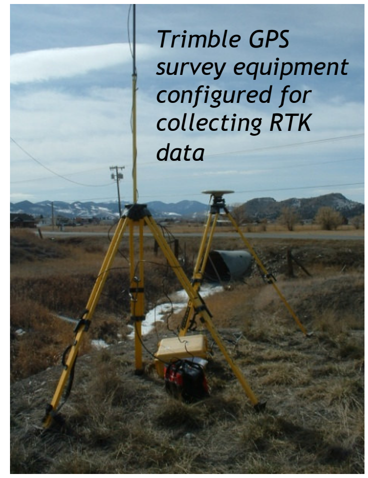

Trimble GPS survey equipment configured for collecting RTK data

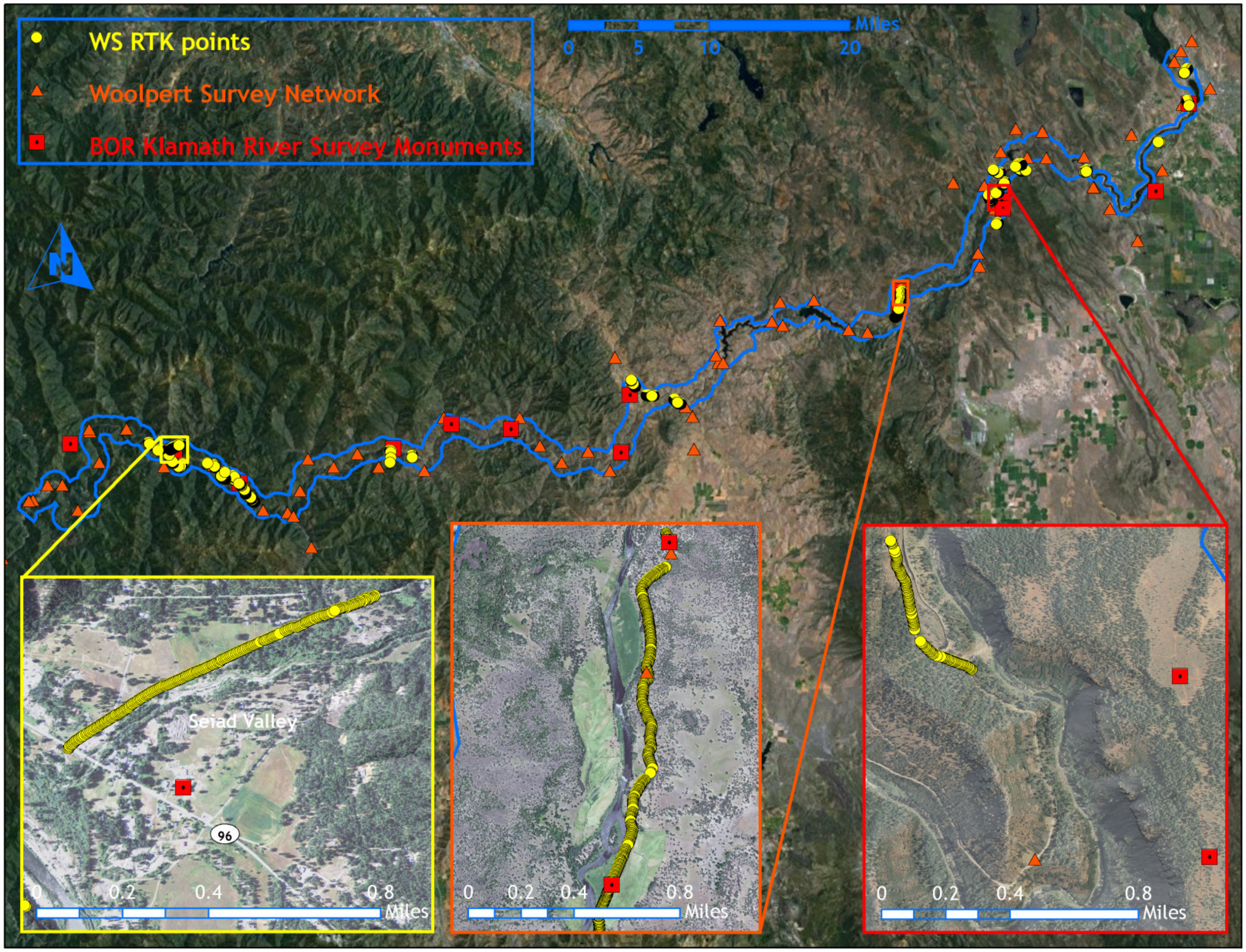
Table 1. *Bureau of Reclamation Survey Monument coordinates for the Klamath River survey area.*

Monument ID	Datum: NAD83 (CORS91)		NAVD88
	Latitude	Longitude	Local GEOID 09 (m)
HPGN_CA_0201 (MX1298)	41° 50′ 29.51294″	123° 11′ 34.89101″	421.910
NGS_Hamburg (DH6612)	41° 48′ 29.94018″	123° 06′ 12.08865″	448.411
KR_IGD_DB1	41° 50′ 54.41573″	123° 20′ 12.33729″	947.345
KR_IGD_DB2	41° 59′ 08.94197″	122° 11′ 30.34725″	826.650
KR_IGD_DB3	42° 00′ 16.27370″	122° 11′ 14.22017″	871.032
KR_IGD_DB4	42° 05′ 46.83280″	122° 02′ 54.77686″	1270.196
KR_IGD_PWH1	41° 52′ 09.37659″	122° 48′ 40.30179″	552.519
Woolpert_105	42° 05′ 17.55614″	122° 02′ 48.75258″	1305.240
NGS_D785 (NY0733)	42° 06′ 15.32401″	121° 50′ 05.78779″	1246.065
NGS_Memorial (DF9369)	42° 11′ 38.78863″	121° 47′ 14.54797″	1259.037
NGS_Doggett (MX1313)	41° 50′ 38.44026″	122° 53′ 28.70761″	519.865
NGS_5680 (DH6396)	41° 50′ 21.52805″	122° 34′ 36.89727″	750.579
NGS_6140 (DH6397)	41° 53′ 55.73718″	122° 33′ 51.85188″	704.748
NGS_02UF (AF8314)	41° 51′ 50.48124″	122° 43′ 43.47411″	568.170

2.2.2 RTK Survey

WSI collected ground check points in the study area using GPS based real-time kinematic (RTK) surveying. Instrumentation included multiple Trimble DGPS units (R8). RTK surveying allows for precise location measurements with an error (σ) of ≤ 1.5 cm. **Figure 2** below portrays the distribution of RTK checkpoint locations used for the Klamath River survey. The RTK surveys were conducted on hard, flat surfaces and used to assess relative (line-to-line) and vertical accuracy of the LiDAR data.

Figure 2. *Watershed Sciences (WS) RTK checkpoints (2767 total), Klamath River Survey Monuments, and Woolpert, Inc. Local Survey Network sites for the Klamath River survey area.*



3. LiDAR Data Processing

3.1 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. Waypoint GPS v.8.10 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. IPAS v.1.35 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.

3.2 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.

The following processing steps were performed on the data:

- LiDAR points were then 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.

- 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).

- The TerraScan software suite was used for classifying near-ground points (Soininen, 2004). The resulting ground classified points were visually inspected and additional ground point modeling was performed in site-specific areas to improve ground detail.

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. 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. All accuracy assessments were conducted on data with ellipsoid heights prior to final transformation.

4.2 Absolute Accuracy

The vertical accuracy of the LiDAR data is described as the mean and standard deviation (sigma ~ σ) 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 assess accuracy for the LiDAR dataset, WS collected 2,767 RTK points were 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 Klamath River 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 the designated 2600 X 2050 ft. delineation).

5.1 Data Summary

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

	Targeted	Achieved
Resolution:	≥ 0.74 points/ft^2 (8 points/m^2)	0.76 points/ft^2 (8.16 points/m^2)
***Vertical Accuracy (1 σ):**	<15 cm	5.5 cm (0.179 ft.)

* Based on 2767 hard-surface control points

5.2 Data Density/Resolution

The average first return density across the survey area is 0.76 points per square foot (**Table 2**). Although the overall density specification was achieved, some types of surfaces (i.e. dense vegetation, breaks in terrain, steep slopes, and water) may return fewer pulses (delivered density) than the laser originally emitted (native density). The density distribution maps in **Figure 5** identify these areas of lower ground and first return densities.

Data Resolution for the Klamath River survey area:

- Combined Average Point (First Return) Density = 0.76 points/ft^2 (8.16 points/m^2)
- Combined Average Ground Point Density = 0.20 points/ft^2 (2.13 points/m^2)

Figure 3. *Density distribution for ground-classified laser points.*

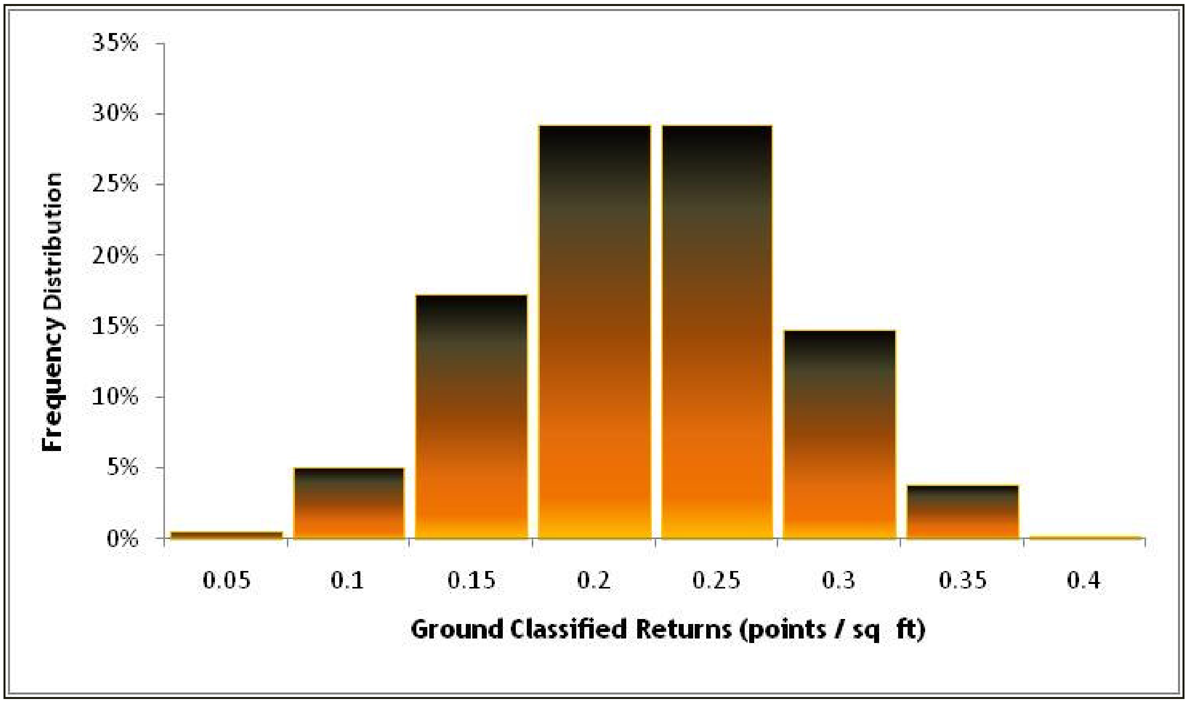


Figure 4. *Density distribution for first return laser points.*

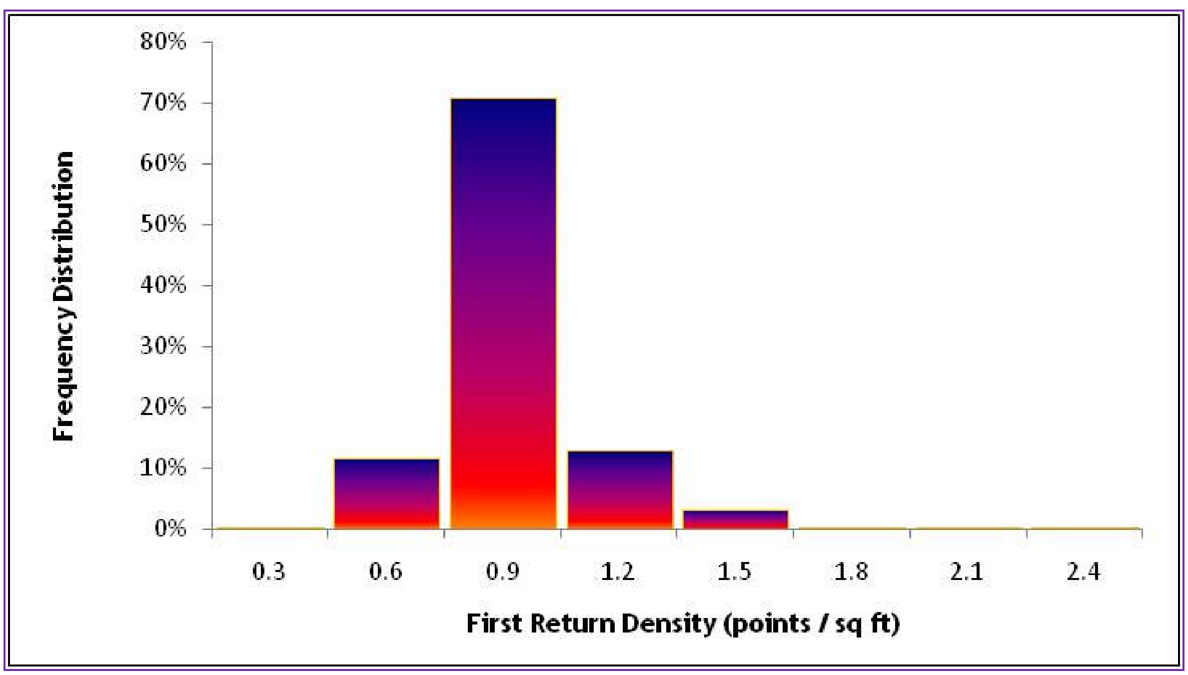


Figure 5. *Klamath River density distribution map for ground-classified laser points.*

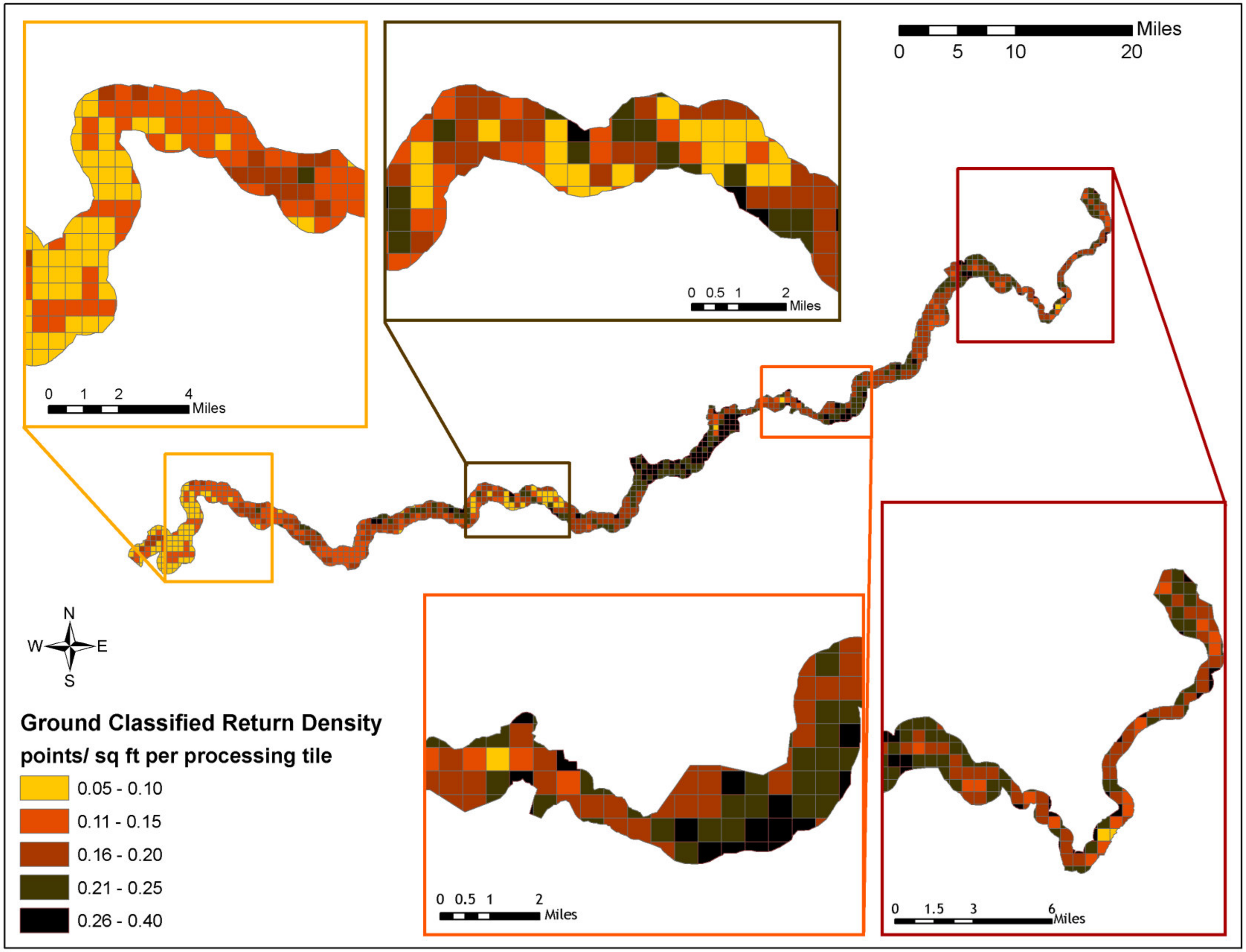
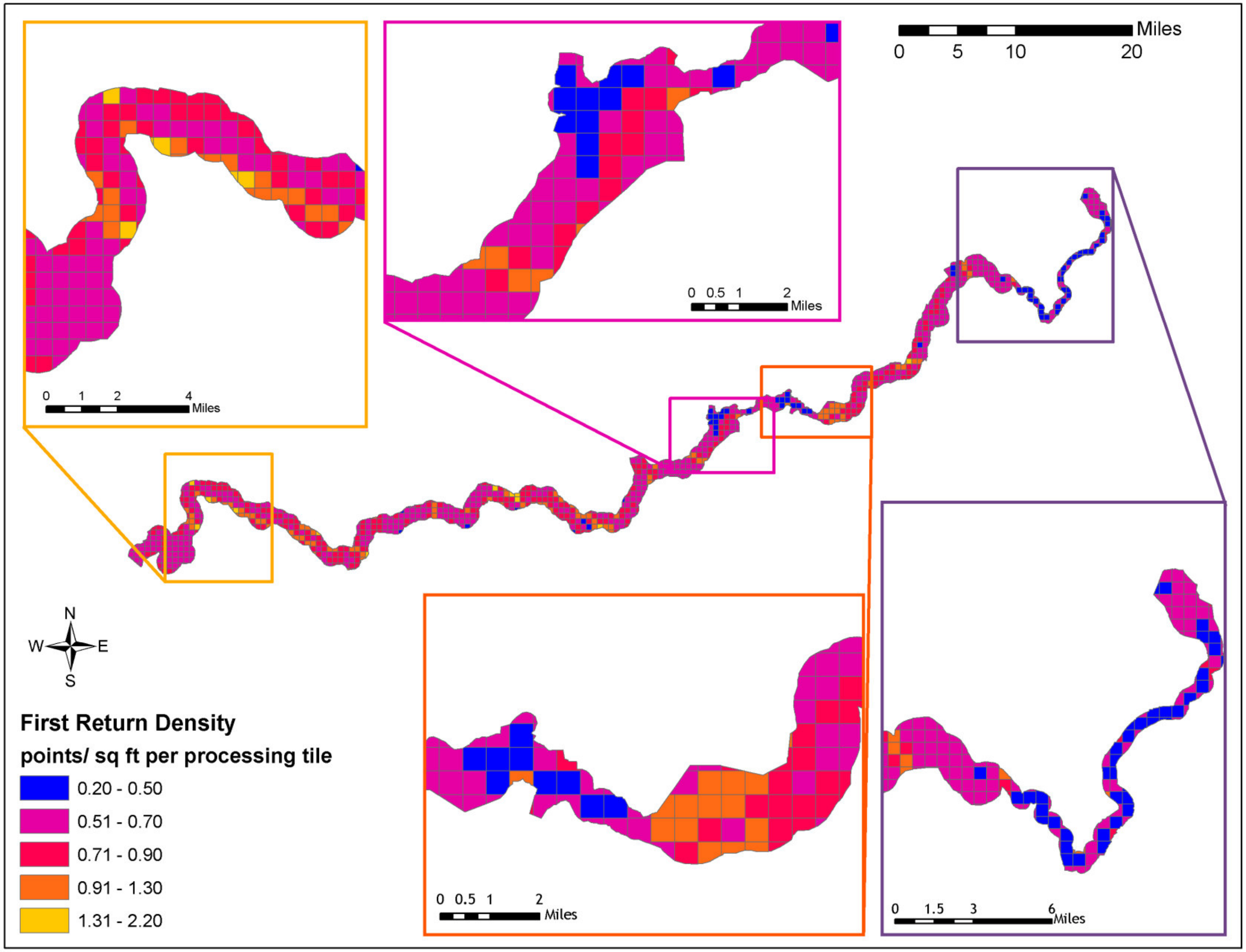


Figure 6. *Klamath River density distribution map for first return laser points.*

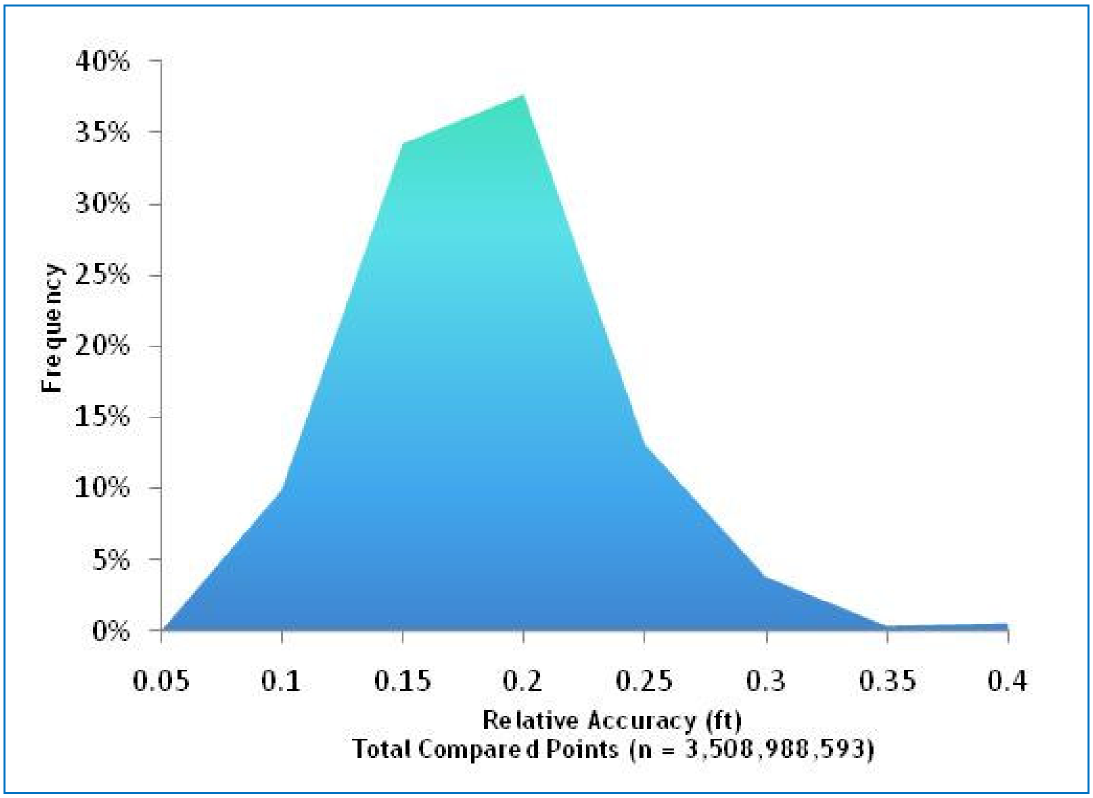

Miles
0
5
10
20
0 0.5 1 2 Miles
0 1 2 4 Miles
N
W
E
S
First Return Density
points/ sq ft per processing tile
0.20 - 0.50
0.51 - 0.70
0.71 - 0.90
0.91 - 1.30
1.31 - 2.20
0 0.5 1 2 Miles
0 1.5 3 6 Miles

5.3 Relative Accuracy Calibration Results

Relative accuracies for the Klamath River survey area:

- Project Average = 0.155 ft (0.047 m)
- Median Relative Accuracy = 0.159 ft (0.048 m)
- 1σ Relative Accuracy = 0.179 ft (0.055 m)
- 2σ Relative Accuracy = 0.248 (0.075 m)

Figure 7*. Distribution of relative accuracies per flight line, non slope-adjusted.*



5.4 Absolute Accuracy

Absolute accuracies for the Klamath River survey area:

***Table 3**. Summary of absolute accuracy statistics.*

RTK Survey Sample Size (n): 2767	
Root Mean Square Error (RMSE) = 0.098 ft (0.030 m)	Minimum Δz = -0.367 ft (-0.112 m)
Standard Deviations:	Maximum Δz = 0.334 ft (0.102 m)
1 sigma (σ) = 0.098 ft (0.030 m) 2 sigma (σ) = 0.193 ft (0.059 m)	Average Δz = 0.013 ft (0.004 m)

***Figure 8**. Absolute Accuracy - Histogram Statistics, based on 2767 hard-surface points.*

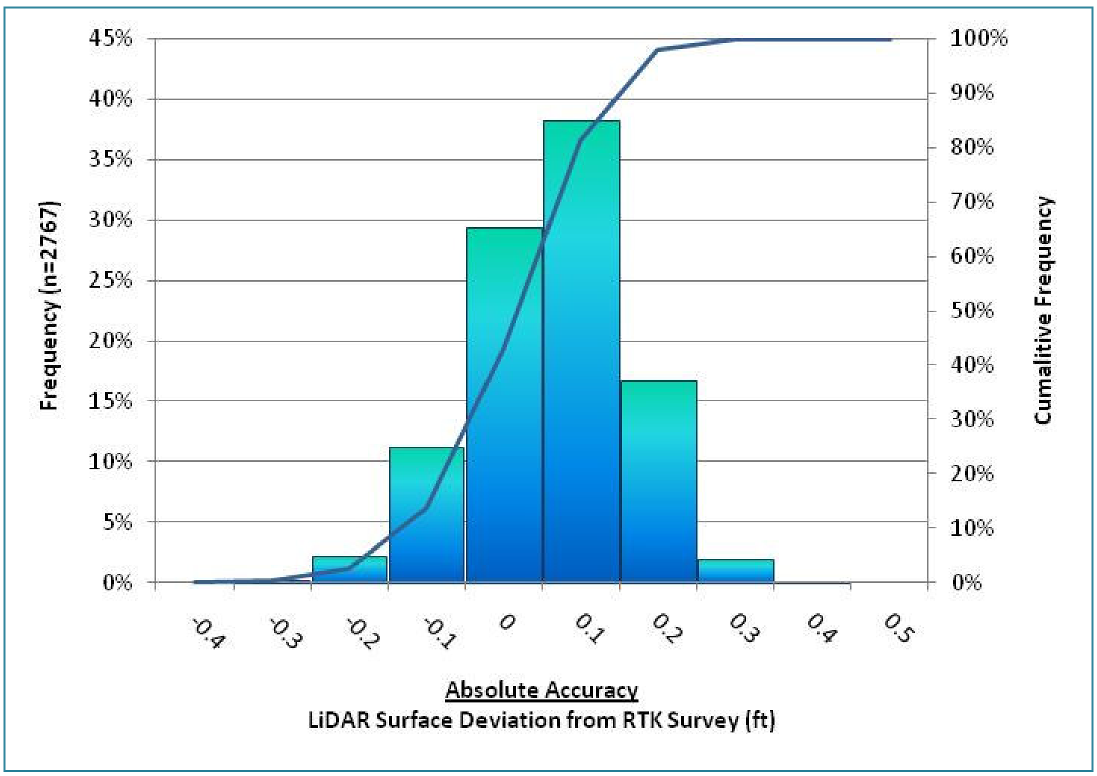
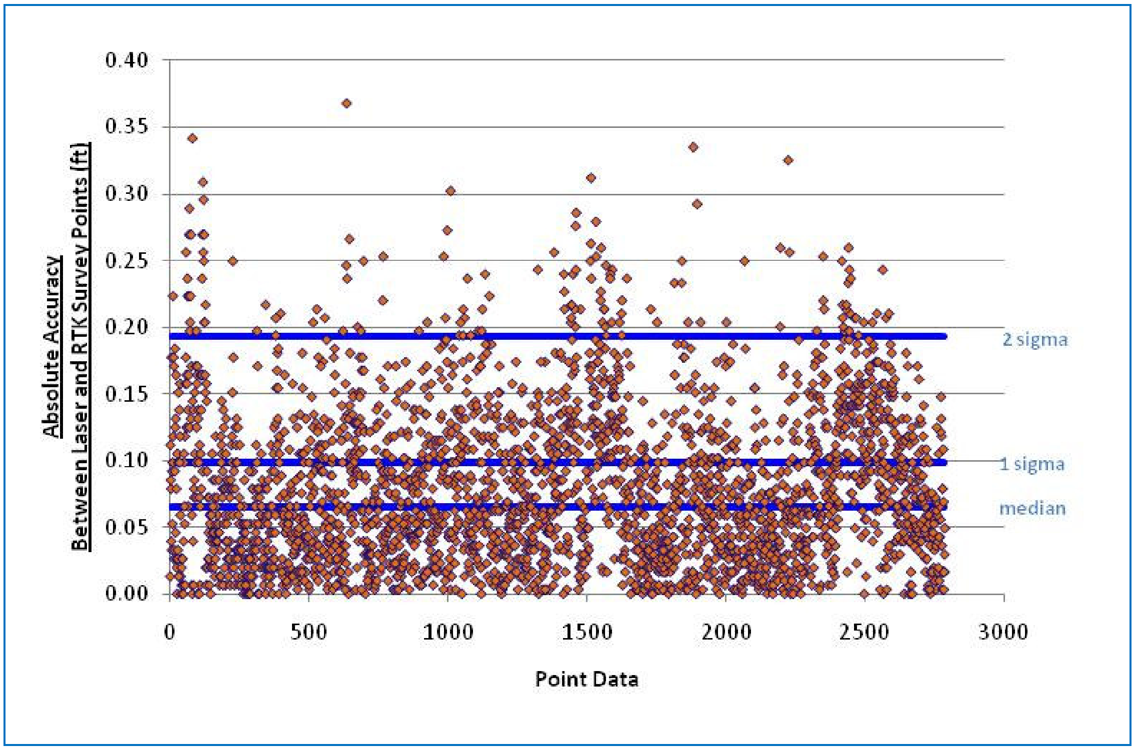


Figure 9. *Absolute Accuracy - Absolute Deviation, based on 2,767 hard surface points.*



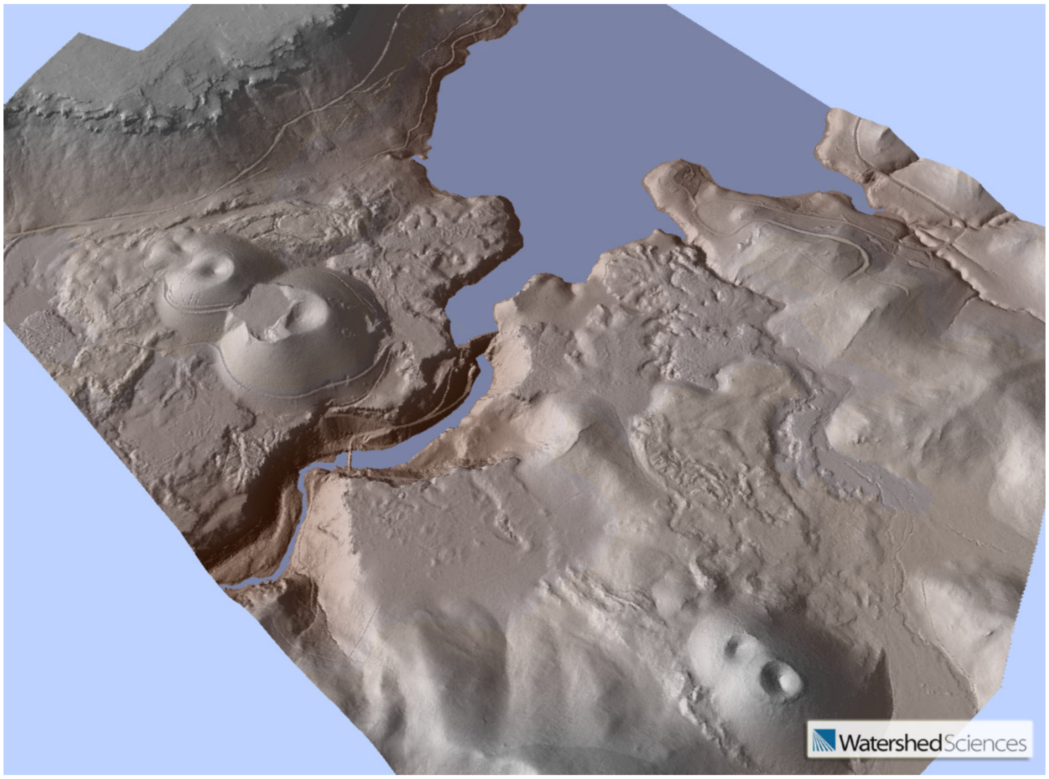
6. Projection/Datum and Units

Projection:		California State Plane, Zone 1 NAD83 (HARN)
Datum	**Vertical:**	NAVD88 Geoid09
	Horizontal:	NAD83
Units:		U.S. Survey Feet

7. Selected Images

***Figure 10**. 3D view looking southeast at the terminus of Upper Klamath Lake, the Klamath Falls, the Link River, and Klamath Falls, Oregon in the background. Top view derived from bare-earth LiDAR model, bottom image derived from highest-hit LiDAR model overlaid with 2006 NAIP imagery.*

***Figure 11**. 3D aerial view of the Klamath River at the Copco Reservoir. Top view derived from bare-earth LiDAR model, bottom image derived from highest-hit LiDAR model.*



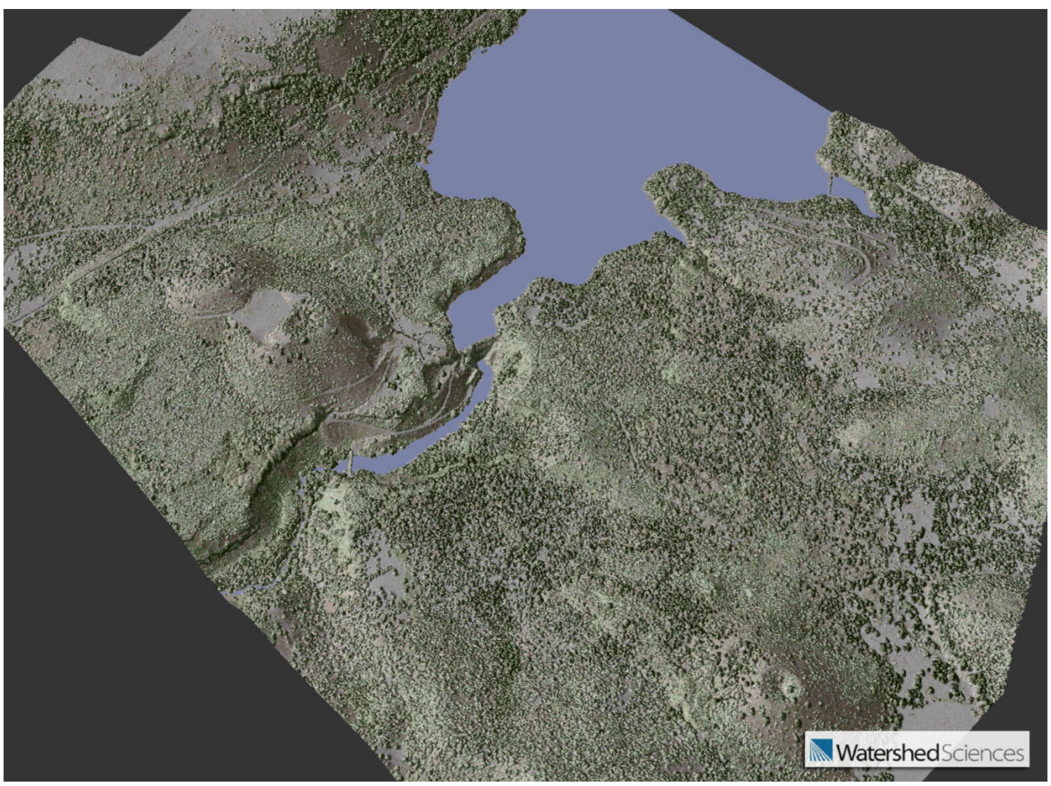
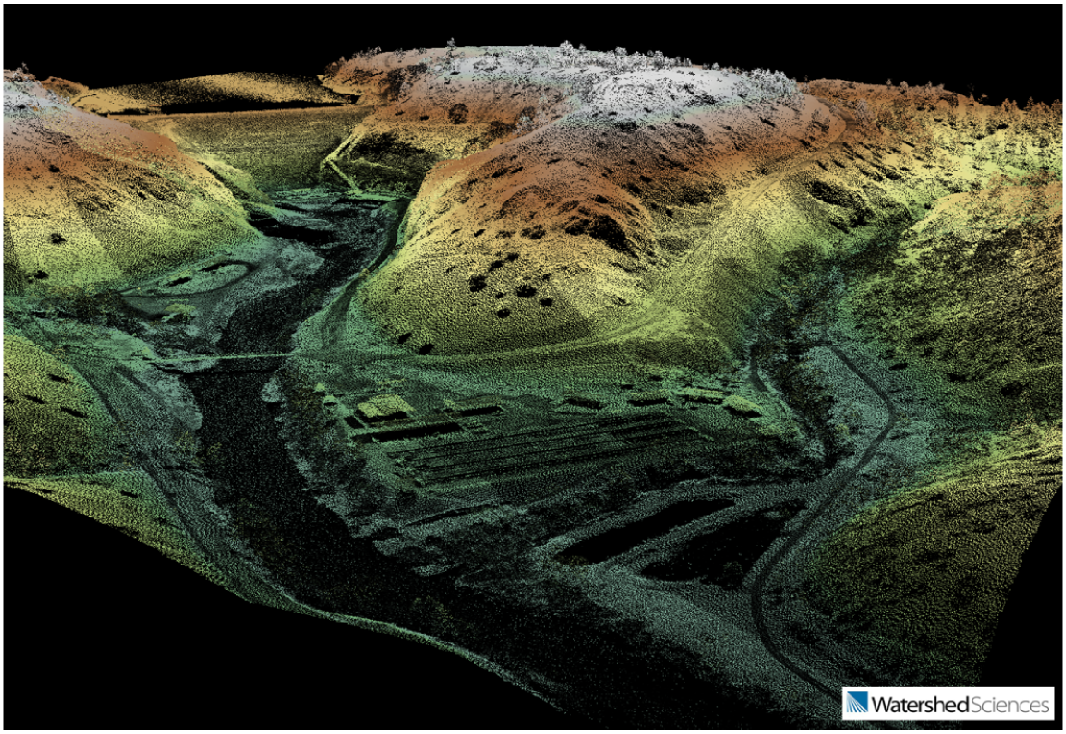


***Figure 12**. 3D Point cloud image derived from LiDAR returns colored by height (top) and overlaid with 2006 NAIP imagery (bottom). The view is looking northeast (upstream) at the confluence of Bogas Creek with the Klamath River (Iron Gate Dam is located in the background).*



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 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, 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.