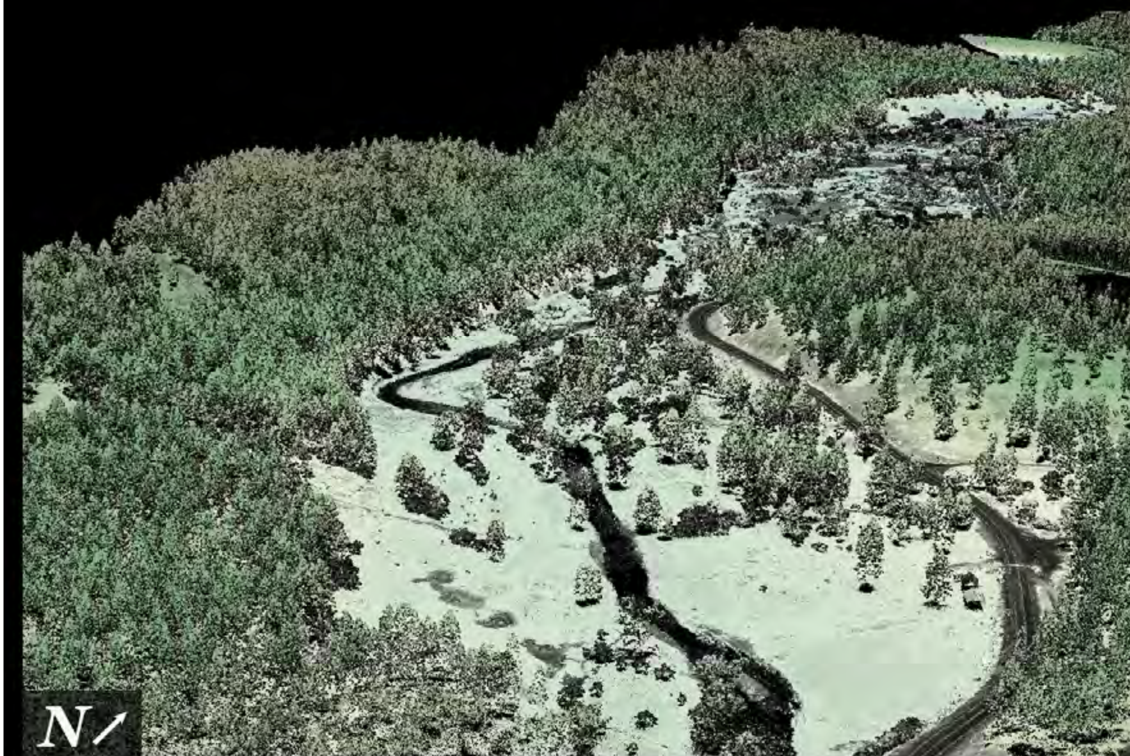
LiDAR Remote Sensing Data Collection:

Desolation Creek, Middle Fork John Day River, & John Day River, Oregon



LiDAR Derived Surface: Point Cloud of all Laser Returns, Shown by Intensity and Elevation, Middle Fork John Day River Study Area

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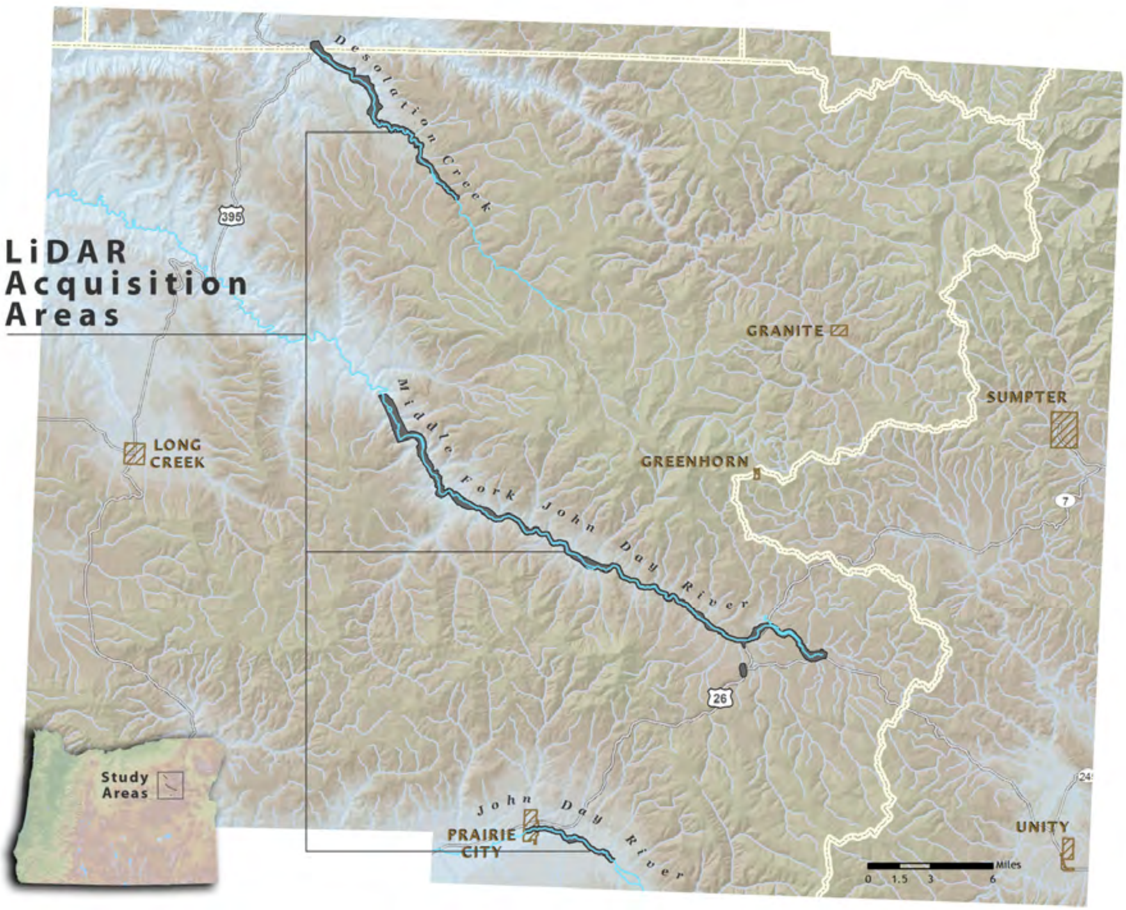
1. Introduction

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data from October 5-7, 2006 for the Puget Sound LiDAR Consortium. The survey areas cover the floodplains of Desolation Creek from the mouth to Bruin Creek; the Middle Fork John Day River from just upstream of Big Creek to Summit Creek; and the John Day River from Prairie City to just above Dans Creek. The study areas total ~9,149 acres (**Figure 1**).

Figure 1. Full extent of all Study Areas: Desolation Creek, Middle Fork John Day, and John Day River, totaling 9,149 acres.



Laser points were collected over the study area using a Leica ALS50 Phase II LiDAR laser system set to acquire points at an average density of ≥8 points per square meter. Full overlap (i.e., ≥50% side-lap) ensured complete coverage and minimized laser shadows created by buildings and tree canopies. A real-time kinematic (RTK) survey was conducted throughout the study area for quality assurance purposes. The accuracy of the LiDAR data is described as standard deviations of divergence (sigma ~ σ) from RTK ground survey points and root mean square error (RMSE) which considers bias (upward or downward).

For the Desolation Creek, Middle Fork John Day River, and John Day River study areas, the data have an RMSE of 0.069 meters, a 1-sigma absolute deviation of 0.069 meters and a 2-sigma absolute deviation of 0.138 meters. Deliverables include point data in ASCII and *.las v.1.1

format, 1- meter resolution laser intensity images, 1-meter resolution bare ground model ESRI GRIDs, and 1-meter resolution Highest Hit vegetation model ESRI GRIDs for the entire study area. All data are delivered in Universal Transverse Mercator (UTM) Zone 11, in the NAD83/NAVD88 datum (Geoid 03).

2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey utilized a Leica ALS50 Phase II mounted in a Piper Aztec. The survey was conducted October 5-7, 2006 (Julian Days 279-280, GSP week 1395).

The Leica ALS50 system was set to acquire 115,000 laser pulses per second (i.e. 115 kHz pulse rate) and flown at 800 meters above ground level (AGL), capturing a scan angle of $\pm 13^{o}$ from nadir[1]. These settings yielded points with an average native density of ≥8 points per square meter. The native pulse density is the number of pulses emitted by the LiDAR system from the aircraft. 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 entire area was surveyed with opposing flight line side-lap of ≥50% (≥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).

2.2 Ground Survey – Instrumentation and Methods

During the LiDAR survey, multiple static (1 Hz recording frequency) ground surveys are conducted over monuments with known coordinates. Coordinates are provided in **Table 1** and locations are shown in **Figures 3-4**. After the airborne survey the static GPS data are 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 reported position accuracy. **Table 1** summarizes the base station coordinates used for kinematic post-processing of the aircraft GPS data.

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

Table 1. Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected).

Datum	NAD83(CORS96)		GRS80
Base Station ID	Latitude (North)	Longitude (West)	Ellipsoid Height (m)
JD1	44°57'38.89072"N	118°55'54.07447"W	1160.753
JD2	44°57'38.93670"N	118°55'52.46293"W	1162.685
MF1	44°37'14.43008"N	118°34'10.27072"W	1193.675
MF2	44°36'44.91972"N	118°32'59.31593"W	1201.925

Multiple Thales Z-max 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 ($\sigma \leq 1.5$ cm ~ 0.6 in). 1,061 RTK ground points were collected throughout the study areas; their locations are shown in **Figure 4**.

Figure 2. RTK surveys utilize a base GPS unit that is set up and connected to a radio and antenna. The roving GPS unit is attached to a field data logger and receives a kinematic correction to collect field RTK data.

Figure 3. Locations of Base Stations and RTK Survey Point Collection: Desolation Creek Study Area, Base Stations JD 1 & 2.

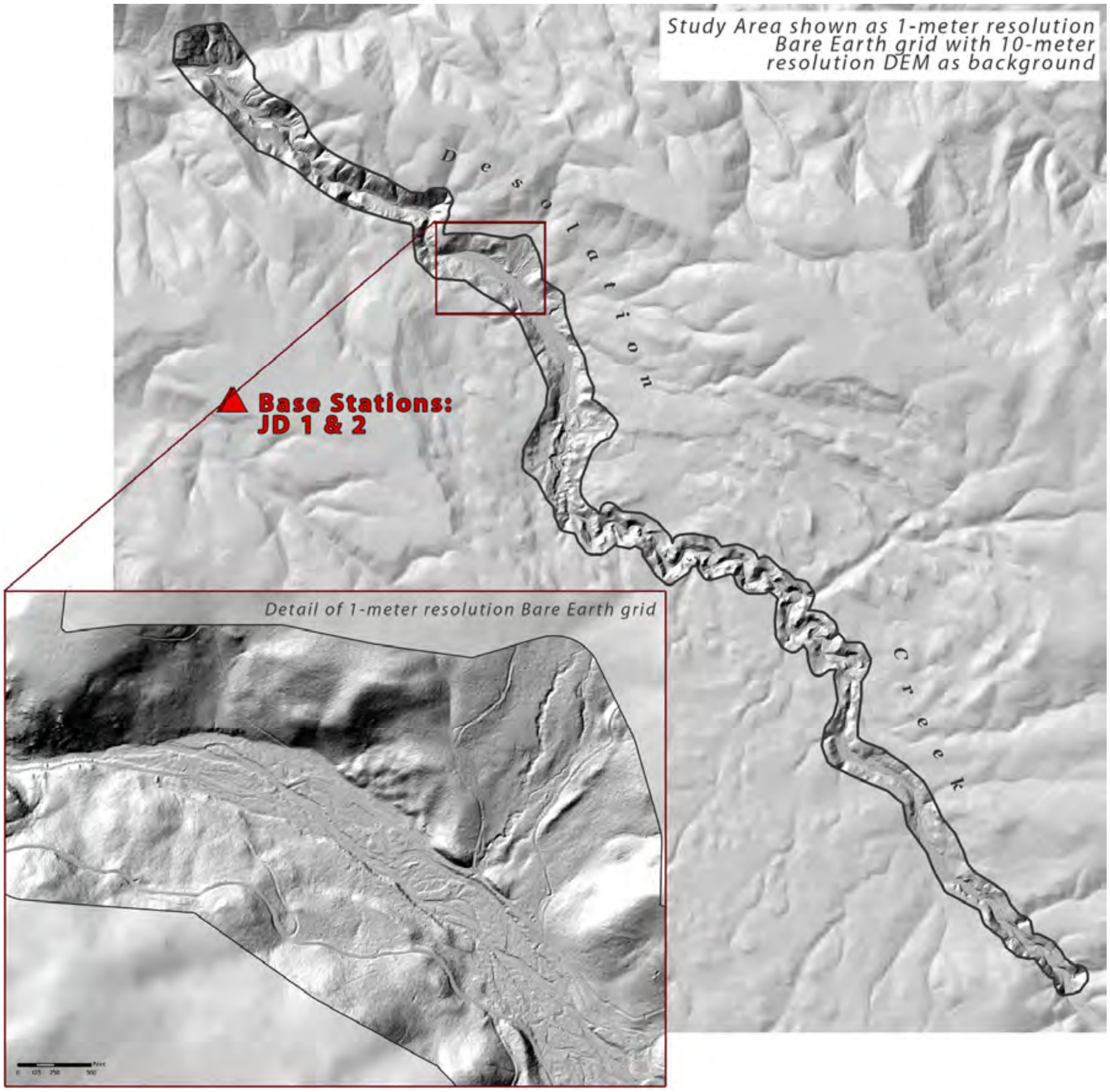
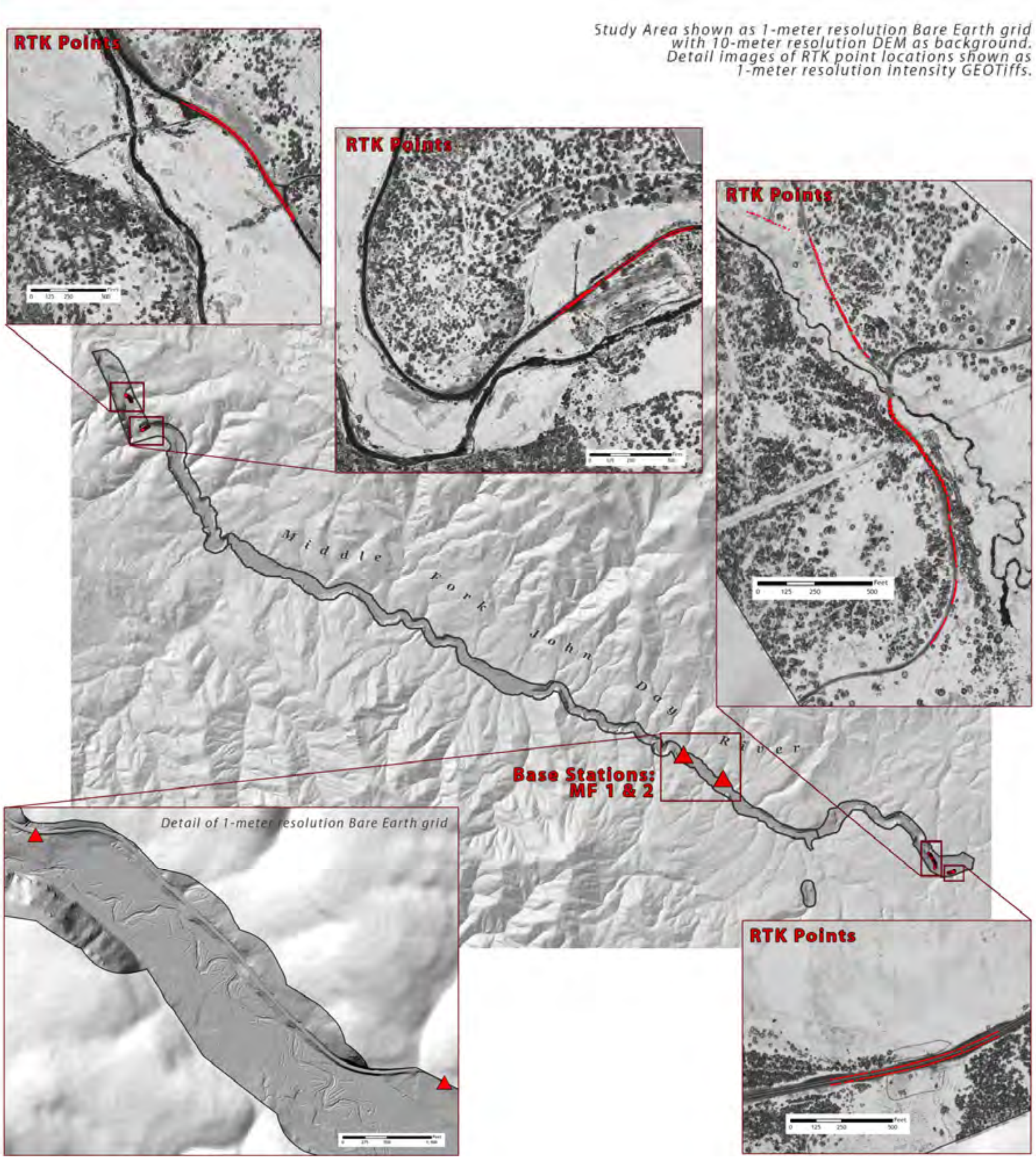


Figure 4. Locations of Base Stations and RTK Survey Point Collection in the Middle Fork John Day Study Area, Base Stations MF 1 & 2, 1061 RTK Points.



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.7.60
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.1.0
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.6.009
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.6.009
6. Position and attitude data are imported. Statistical absolute accuracy is assessed via direct comparisons of laser points to ground RTK survey data. Data are then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction.
   Software: TerraScan v.6.009
7. The bin-delineated LAS files (ASPRS v1.0) are converted to ASCII format, preserving all LAS fields.
   Software: Custom

3.2 Aircraft Kinematic GPS and IMU Data

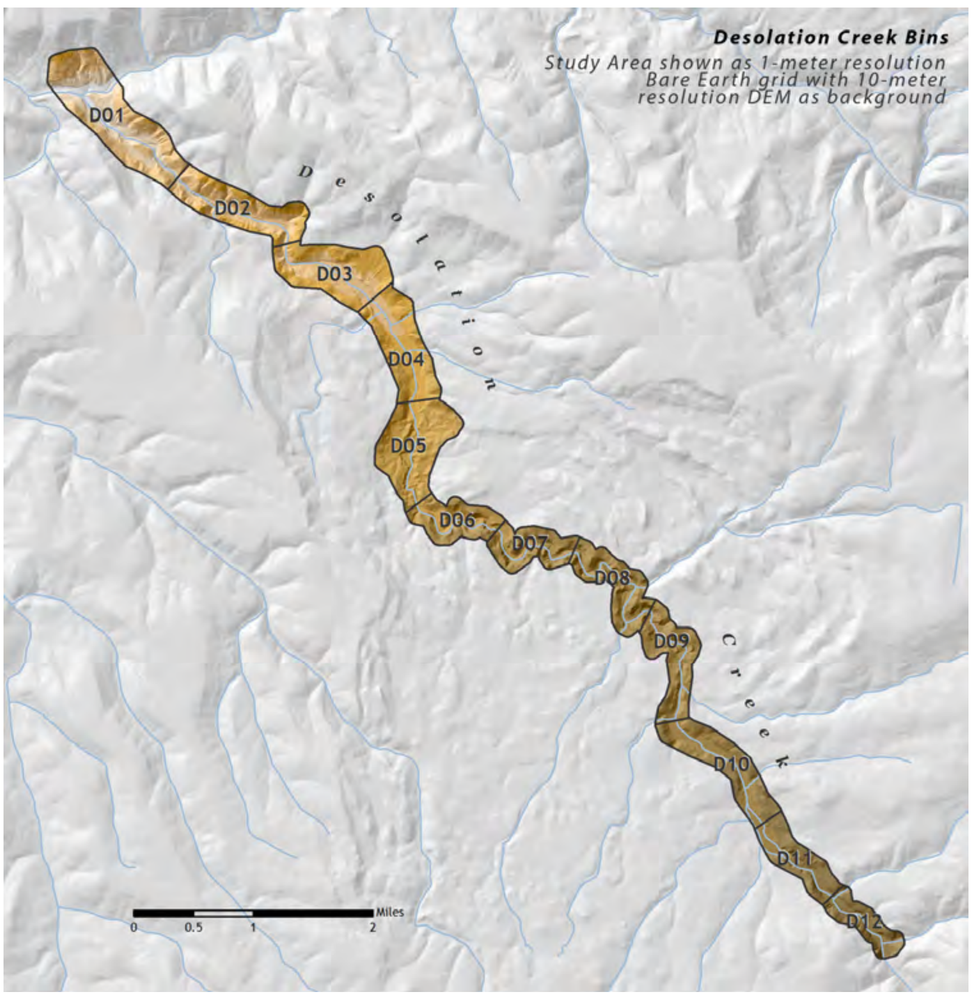
LiDAR survey datasets are referenced to 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collects 2 Hz kinematic GPS data. The onboard inertial measurement unit (IMU) collects 200 Hz aircraft attitude data. Waypoint GPS v.7.60 is used to process the kinematic corrections for the aircraft. The static and kinematic GPS data are then post-processed after the survey to obtain accurate GPS solution and aircraft positions. IPAS v.1.0 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 estimate trajectory (SBET) file that contains accurate and continuous aircraft positions and attitudes.

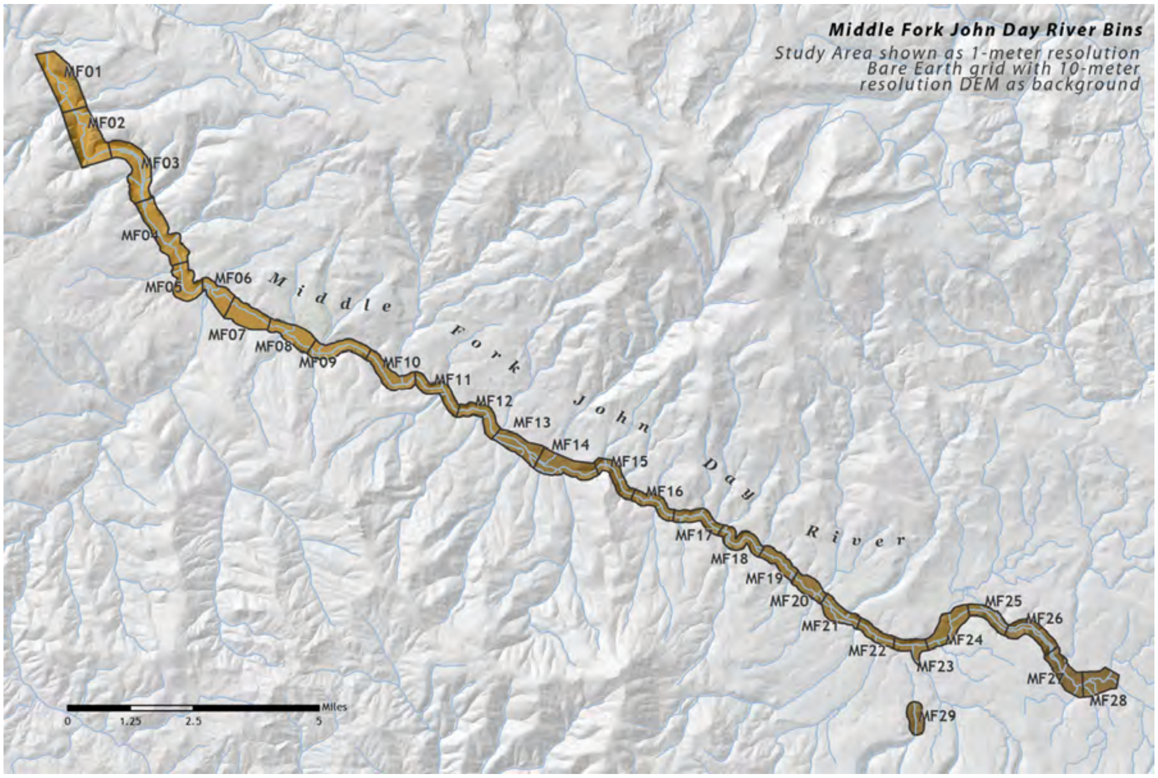
3.3 Laser Point Processing

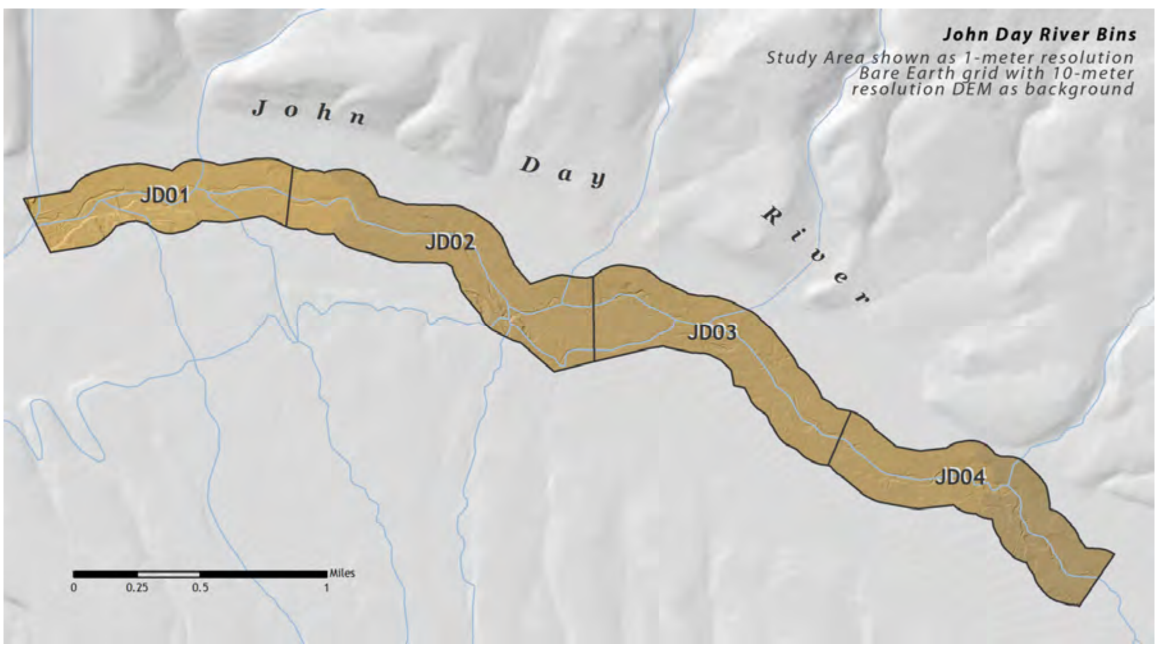
Laser point coordinates are computed using the IPAS software suite based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) are assigned an associated (x, y, z) coordinate along with unique intensity values (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 (i.e. > 40 GB). To facilitate laser point processing, bins (polygons) are created to divide the dataset into manageable sizes (less than 500 MB). The study areas are divided into individual bins, as shown in **Figure 5** below.

Figure 5: Bin delineations of Desolation Creek, Middle Fork John Day River, and John Day River study areas.







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 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 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 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 reclassified as non-grounds. Ground surface raster and contour vector data are developed from triangulated irregular networks (TINs) of ground points.

3.4 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**: 1,061 RTK GPS measurements were compared to the LiDAR point data. <u>The root mean square error (RMSE) for the study areas is 0.069 meters, the 1-sigma absolute deviation is 0.069 meters and the 2-sigma absolute deviation is 0.138 meters</u>.

Table 2. 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	Effect
GPS (Static/Kinematic)	Long Base Lines	None	
	Poor Satellite Constellation	None	
	Poor Antenna Visibility	Reduce Visibility Mask	Slight
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings	Large
	Inaccurate System	None	
Laser Noise	Poor Laser Timing	None	
	Poor Laser Reception	None	
	Poor Laser Power	None	
	Irregular Laser Shape	None	

3.4.1 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 800 meters above ground level (AGL) flight altitude. Laser horizontal errors are a function of flight altitude above ground (i.e., ~ 1/3000th 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 ±13^{o} 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 less than 3.0). Before each flight, the PDOP (Position Dilution of Precision) was determined for the survey day. During all flight times, two (2) dual frequency DGPS base stations recording at 1-second epochs were utilized and a maximum baseline length between the aircraft and the control points was less than 24 km (15 miles) at all times.
5. Ground Survey: Ground survey points 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. The ground survey collected 1061 RTK points distributed throughout multiple flight lines.
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 as 1σ of 10.9 cm (see **Figure x**).

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. The resulting overlapping ground points (per line) total over 419 million points from which to compute and refine relative accuracy. 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. After the automated attitude calibration was completed the resulting relative accuracy was a 1σ of 0.065m. 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. The corrections create a slight improvement and the resulting relative accuracy is a 1σ of 0.065 m. Automated Z calibration is the final step employed for relative accuracy calibration.

Figure 6. Relative accuracy per flight line with overlapping point totals listed as 'n'.

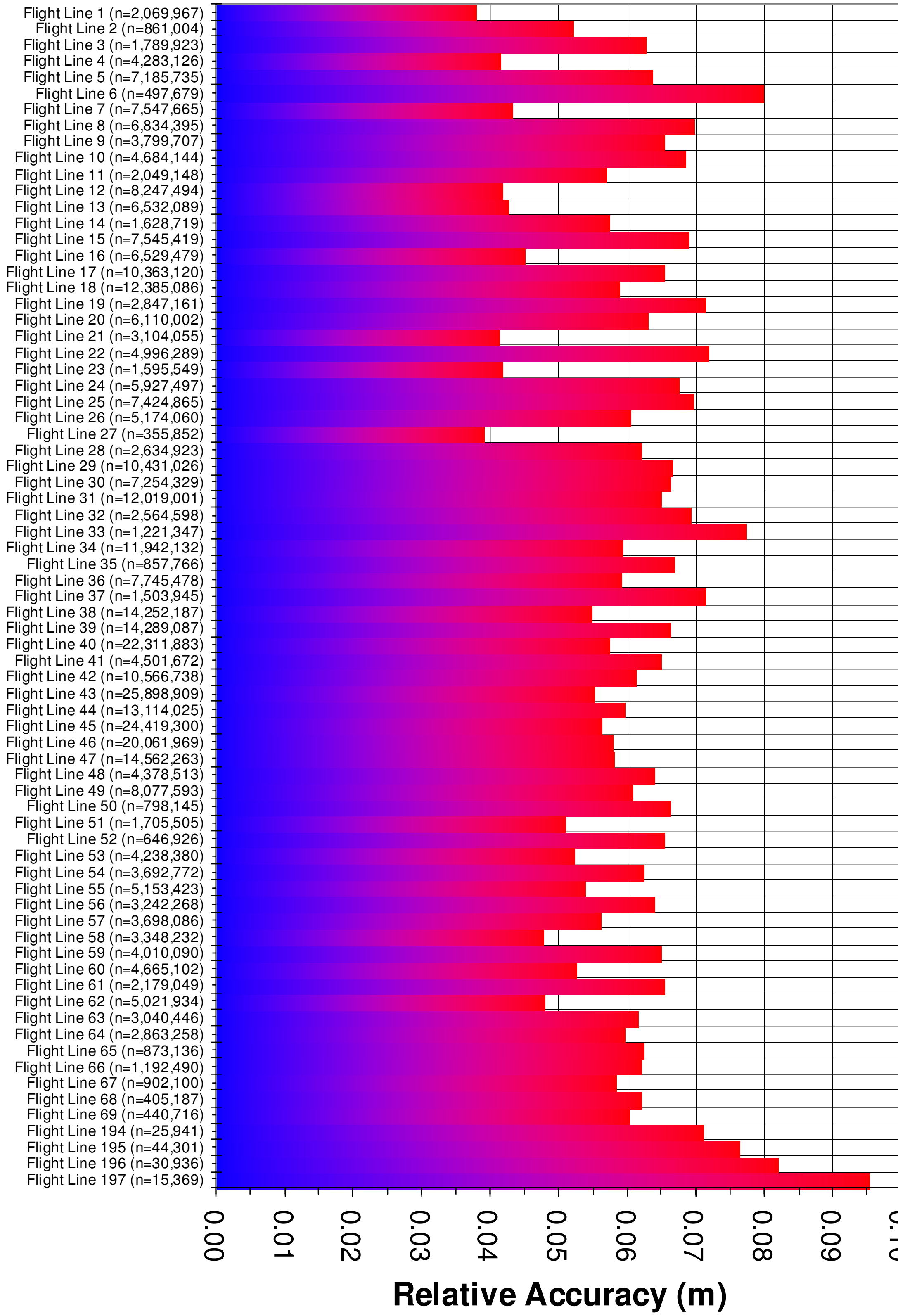


Figure 7. Distribution of relative accuracies per flight line.

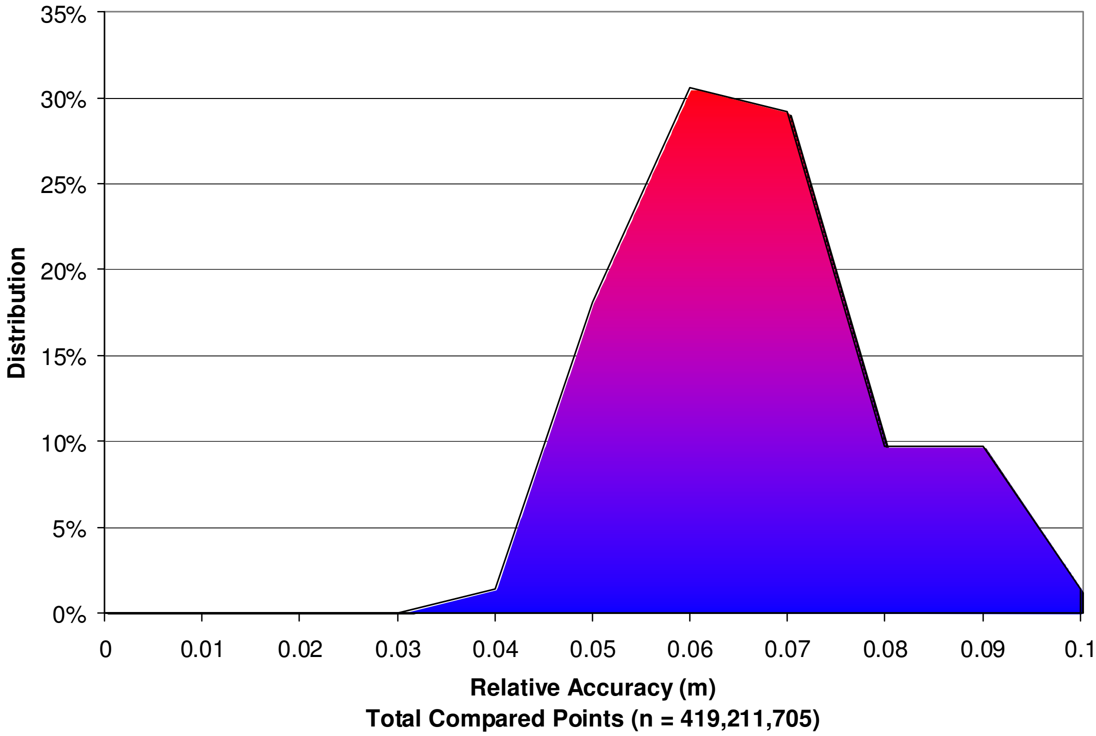
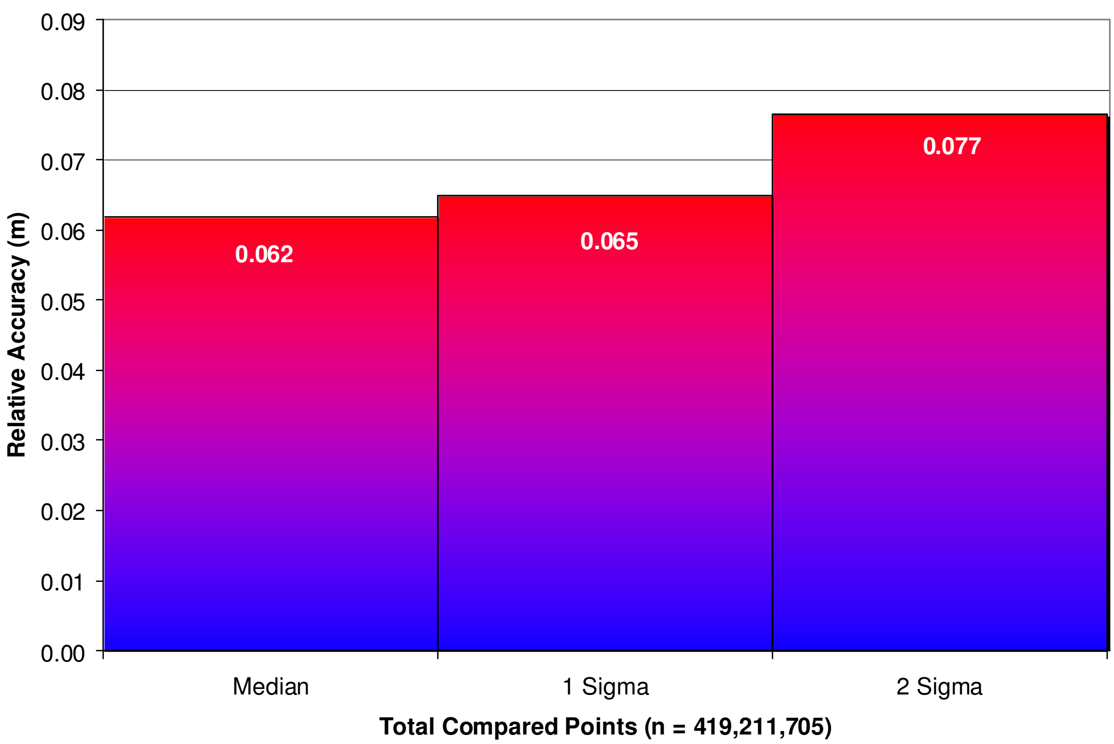


Figure 8. Statistical relative accuracies.



3.4.2 Absolute Accuracy

The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. Accuracy statistics are reported in **Table 3** and shown in **Figures 6-7**.

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

Sample Size (n): 1061

Root Mean Square Error (RMSE): 0.063 meters

Standard Deviations	Deviations
1 sigma (σ): 0.069 meters	**Minimum Δz:** -0.17 meters
2 sigma (σ): 0.138 meters	**Maximum Δz:** 0.18 meters
	Average Δz: 0.00 meters

Figure 9. Histogram Statistics

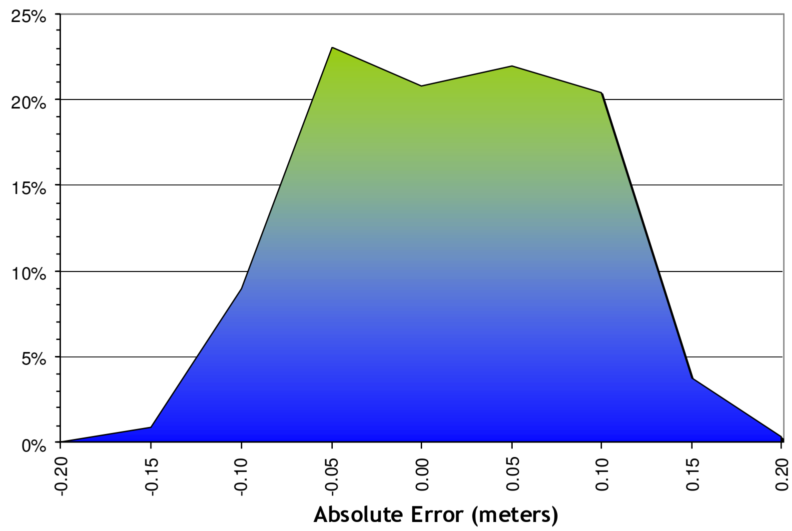
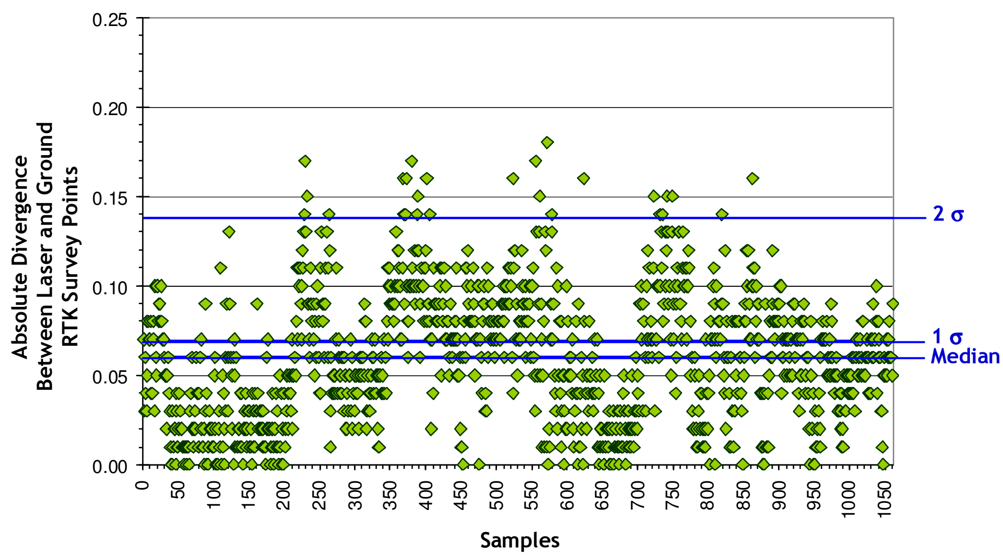


Figure 10. Point Absolute Deviation Statistics



3.5 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 Geiod03 model is applied to each point. The data were processed using meters in the Universal Transverse Mercator (UTM) Zone 11 and NAD83 (CORS96)/NAVD88 datum.

4. Deliverables and Specifications

Table 4. LiDAR Data Specifications

John Day River Study Areas: ***Desolation Creek, Middle Fork John Day River, John Day River***		
Resolution & Accuracy	Native Pulse Density	≥8 pulses/m^2
	Vertical RMSE of LiDAR Survey	0.069 meters
	RTK Data RMSE	≤.015 meters
	RTK Quality Control Data Points Collected	1,061
Projection & Datum	Coordinate System	Universal Transverse Mercator (UTM) Zone 11
	Horizontal datum	NAD83 (CORS96)
	Vertical datum	NAVD88 (Geoid03)
Key Acquisition Parameters	Laser Pulse Rate	115,000 pulses per second
	Number of Returns Collected Per Laser Pulse	Up to 4
	Scan Angle	±13^{o} from Nadir
	Adjacent Swath Overlap (Side-Lap)	≥50%

4.1 Point Data (per bin)

- LAS format V. 1.1
- ASCII space delimited
    - All points
    - Bare Earth points

4.2 Vector Data

- Bin delineations for all study areas in shapefile format
- SBET (Smooth Best Estimated Trajectory, 5Hz)

4.3 Raster Data (per study area)

- ESRI GRIDs of LiDAR dataset:
    - Bare Earth Modeled Points (1-meter resolution),
    - Vegetation Modeled Points- Highest Hit model (1-meter resolution),
- Surface intensity images in GEOTIFF format (1-meter resolution),

4.4 Data Report

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

5. Selected Images

5.1 Plan View Data

An example area is presented to show the following plan view datasets (see **Figures 8-10**):

- Bare earth 1-meter pixel resolution ESRI Grids,
- Highest Hit vegetation 1-meter resolution ESRI Grids, and
- Intensity image 1-meter pixel GeoTIFFs

5.2 Three Dimensional Oblique View Data Pairs

Example areas are presented to show paired 3-D oblique view imagery of the same scene. These pairs depict a triangulated irregular network (TIN) model of ground-classified LiDAR points colored by elevation (top image), and a point cloud of all points colored by elevation and intensity shading (bottom image). *Please note that the oblique view images are not always north-oriented.*

Figure 11. Bare Earth 1-meter resolution ESRI grid showing detail in **Desolation Creek Study Area** (bins D10-D11).

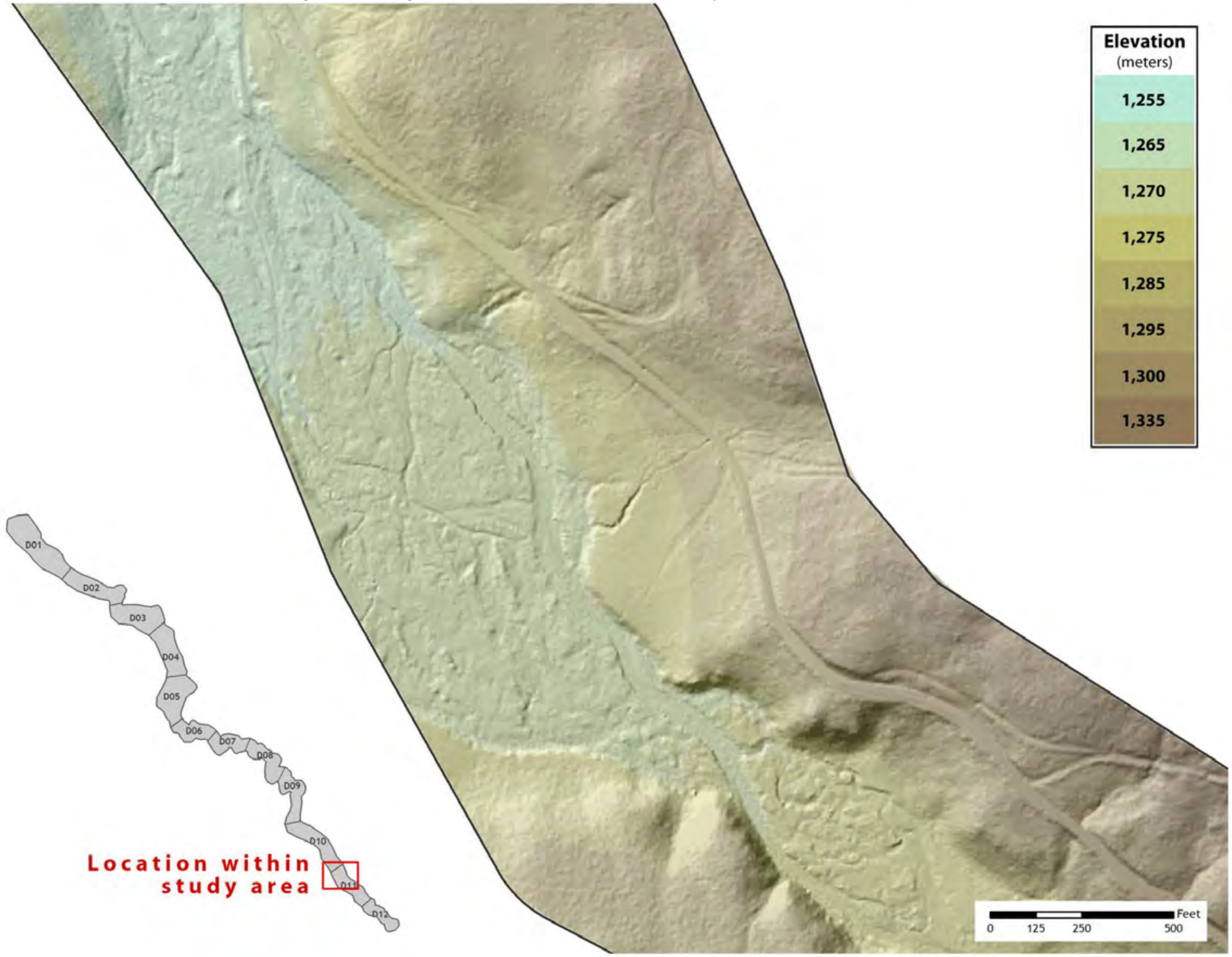


Figure 12. The Highest Hit 1-meter resolution ESRI grid showing detail in **Desolation Creek Study Area** (bins D10-D11). To calculate vegetation heights, the Bare Earth grid was subtracted from the Highest Hit grid.

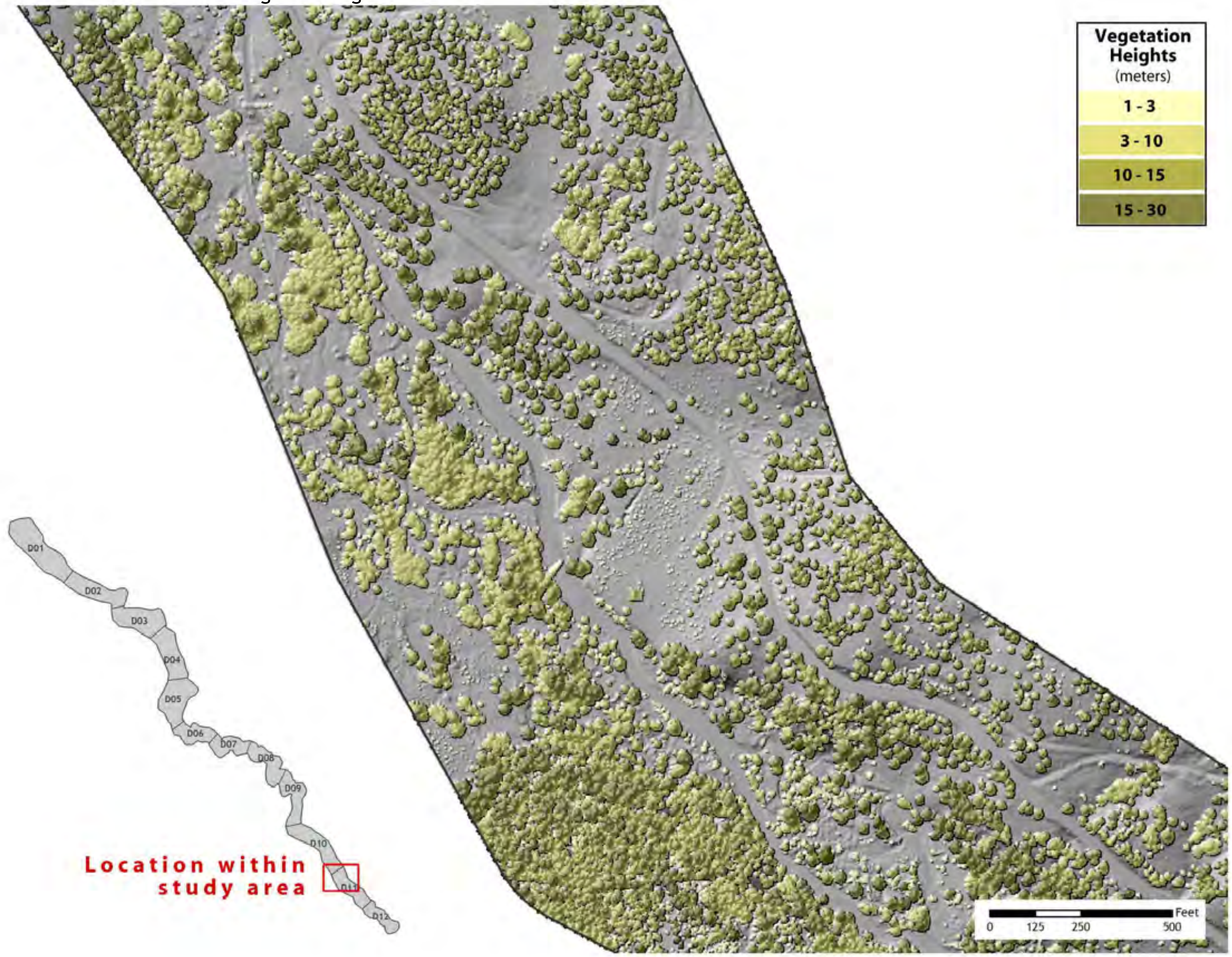


Figure 13. 1-meter resolution intensity image showing detail in **Desolation Creek Study Area** (bins D10-D11).

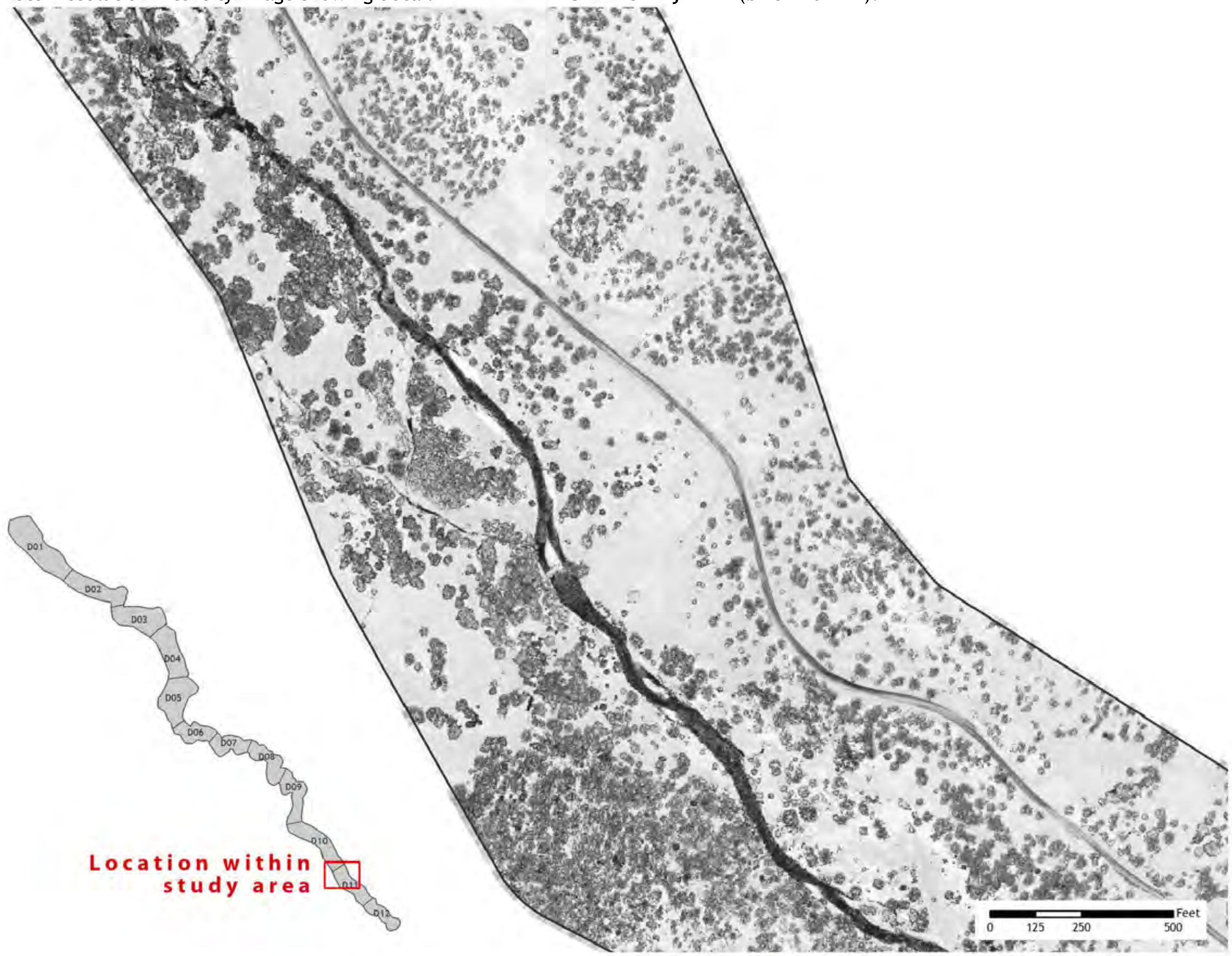


Figure 14. 3-d oblique view of LiDAR-derived surfaces in bins D04-D05 of the **Desolation Creek Study Area** (top image derived from ground-classified points, bottom image derived from all points).

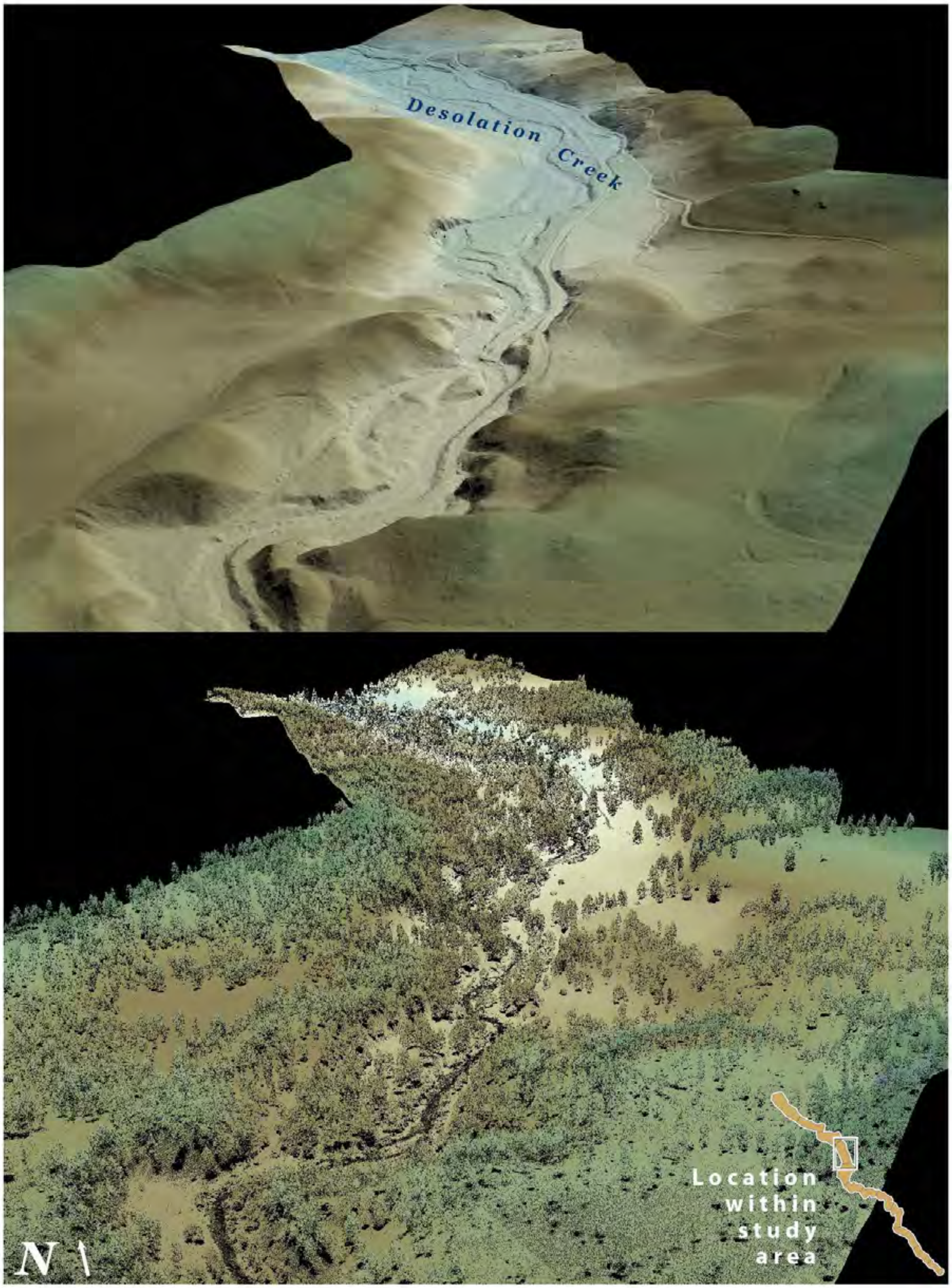


Figure 15. 3-d oblique view of LiDAR-derived surfaces in bins MF03-MF04 of the **Middle Fork John Day River Study Area** (top image derived from ground-classified points, bottom image derived from all points).

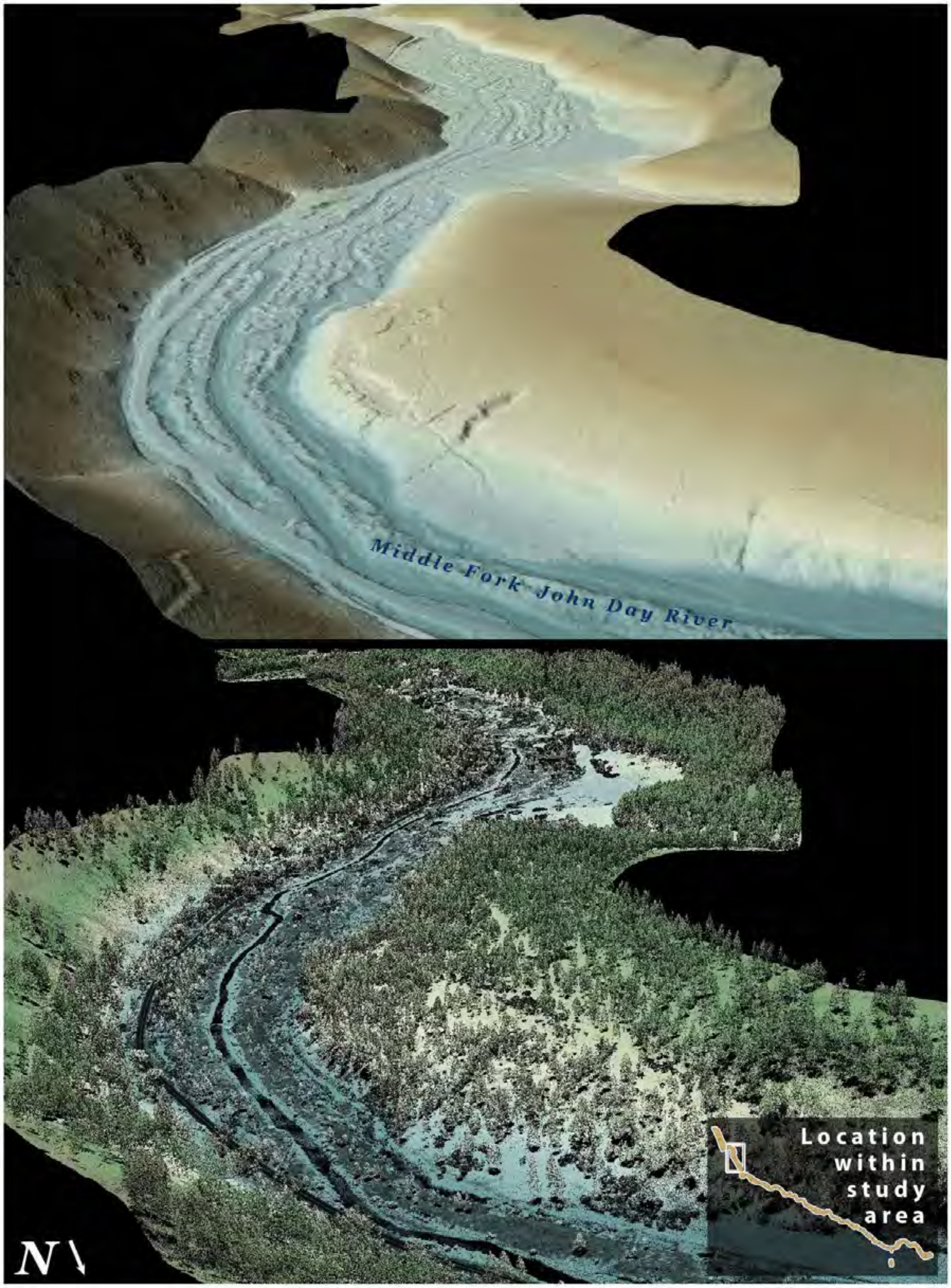


Figure 16. 3-d oblique view of LiDAR-derived surfaces in bins MF23-MF24 of the **Middle Fork John Day River Study Area** (top image derived from ground-classified points, bottom image derived from all points).

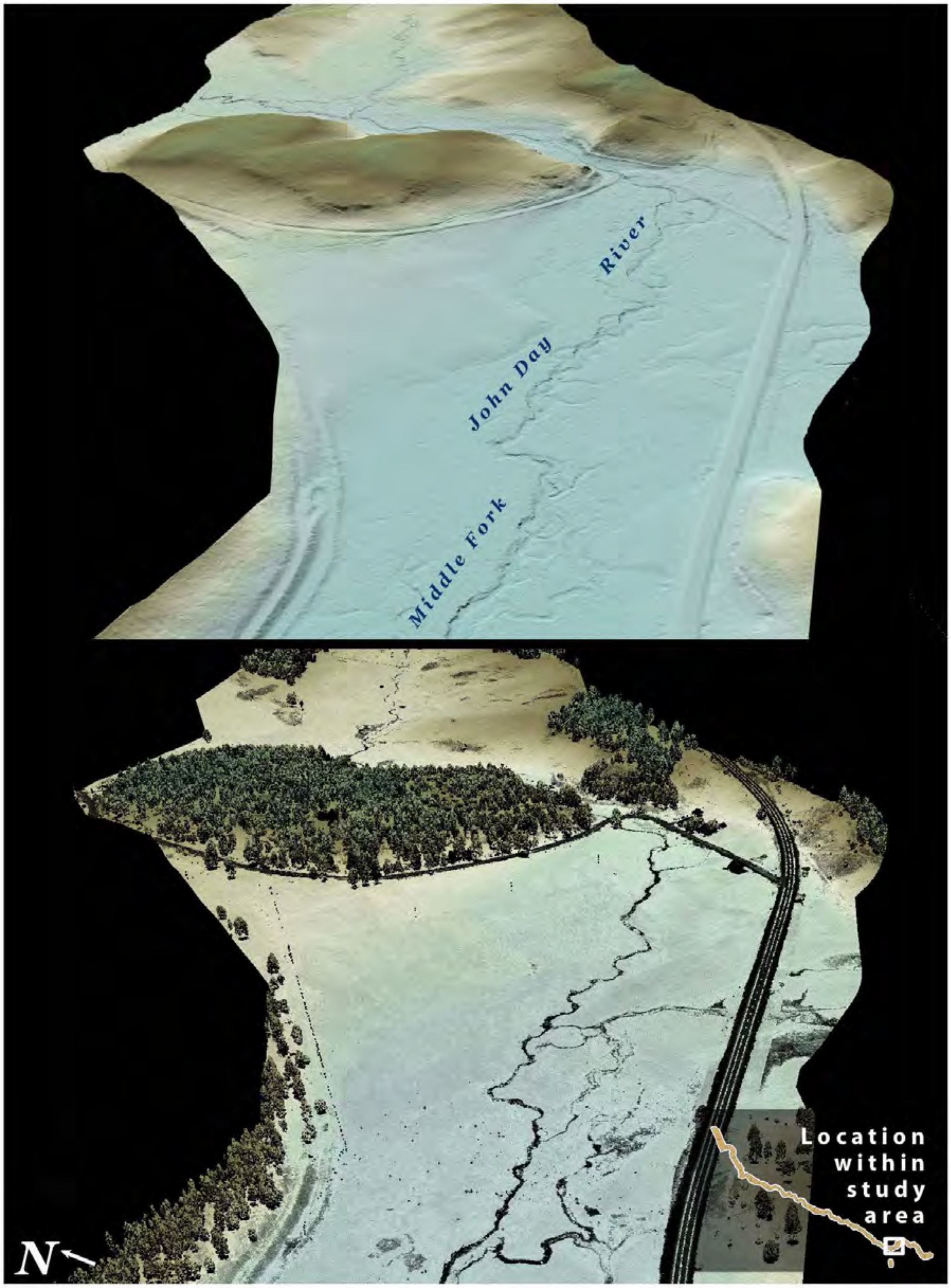
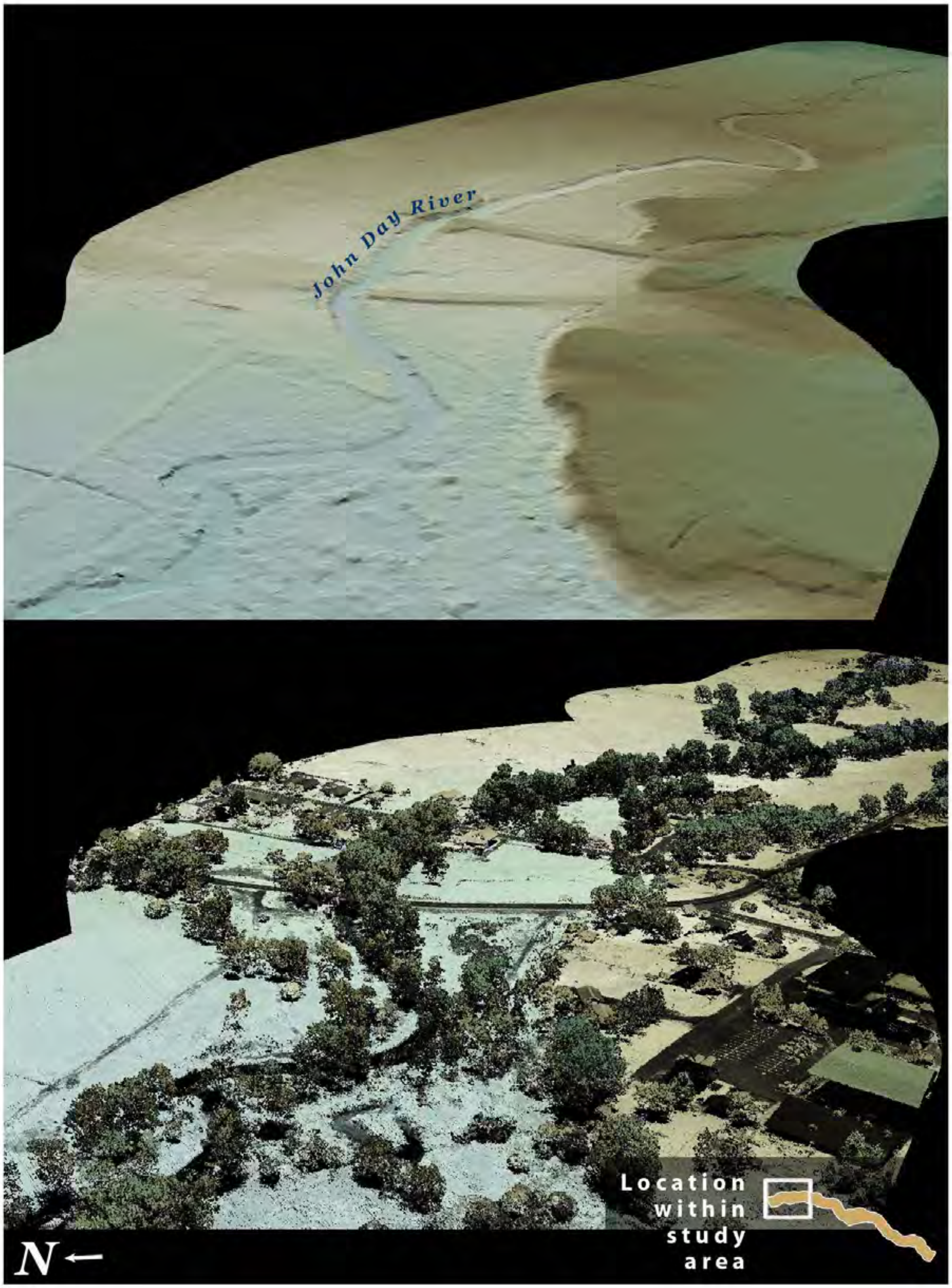


Figure 17. 3-d oblique view of LiDAR-derived surfaces in bin JD01 of the **John Day River Study Area** (top image derived from ground-classified points, bottom image derived from all points).



6. Glossary

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68^{th} percentile) of a normally distributed data set.

2-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95^{th} 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. Calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Pulse Repetition Frequency (PRF): 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 Optech ALTM 3100 LiDAR 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.

7. Citations

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