Applied Remote Sensing and Analysis

November 1, 2013

Birch Creek Streams

LiDAR and Digital Imagery Report

Greg Silbernagel
Umatilla Basin Watershed Council
Pendleton, OR
PH: 541-276-2190

WSI Corvallis Office
517 SW 2nd St., Suite 400
Corvallis, OR 97333
PH: 541-752-1204

Table of Contents

Cover Photo: View looking north over Bear Creek. The bare-earth gridded model and vegetation point cloud are draped with 15 cm orthoimagery.

INTRODUCTION

View of the Trimble GPS equipment set up in the mixed grasslands near the Birch Creek Streams sites in Oregon.

In August 2013, WSI (Watershed Sciences, Inc.) was contracted by the Umatilla Basin Watershed Council (UBWC) to collect Light Detection and Ranging (LiDAR) data and digital imagery in the fall of 2013 for three sites within the Umatilla Basin Watershed: Birch Creek Streams, Meacham Creek, and Dillon Dam in Oregon. Data were collected to aid the UBWC in assessing the topographic and geophysical properties of the Birch Creek Streams sites in Oregon to support aquatic habitat restoration and analysis.

This report accompanies the delivered LiDAR data, as well as imagery acquired and processed by 3Di (Eugene, OR) in association with WSI. Data acquisition procedures, processing methods, and results of all accuracy assessments are documented in this report. Project specifics are shown in Table 1, the project extent can be seen in Figure 1, and a complete list of contracted deliverables provided to UBWC can be found in Table 2.

Table 1: Acquisition dates, acreages, and data types collected on the Birch Creek Streams site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Birch Creek Streams	16,098	28,911	08/22/2013 – 08/25/2013	LiDAR
			09/13/2013	4 band (RGB) Digital Imagery *(collected and processed by 3Di)*
Dillon Dam Meacham Creek	2,827	4,346	08/26/2013	LiDAR
			09/13/2013	4 band (RGB) Digital Imagery *(collected and processed by 3Di)*

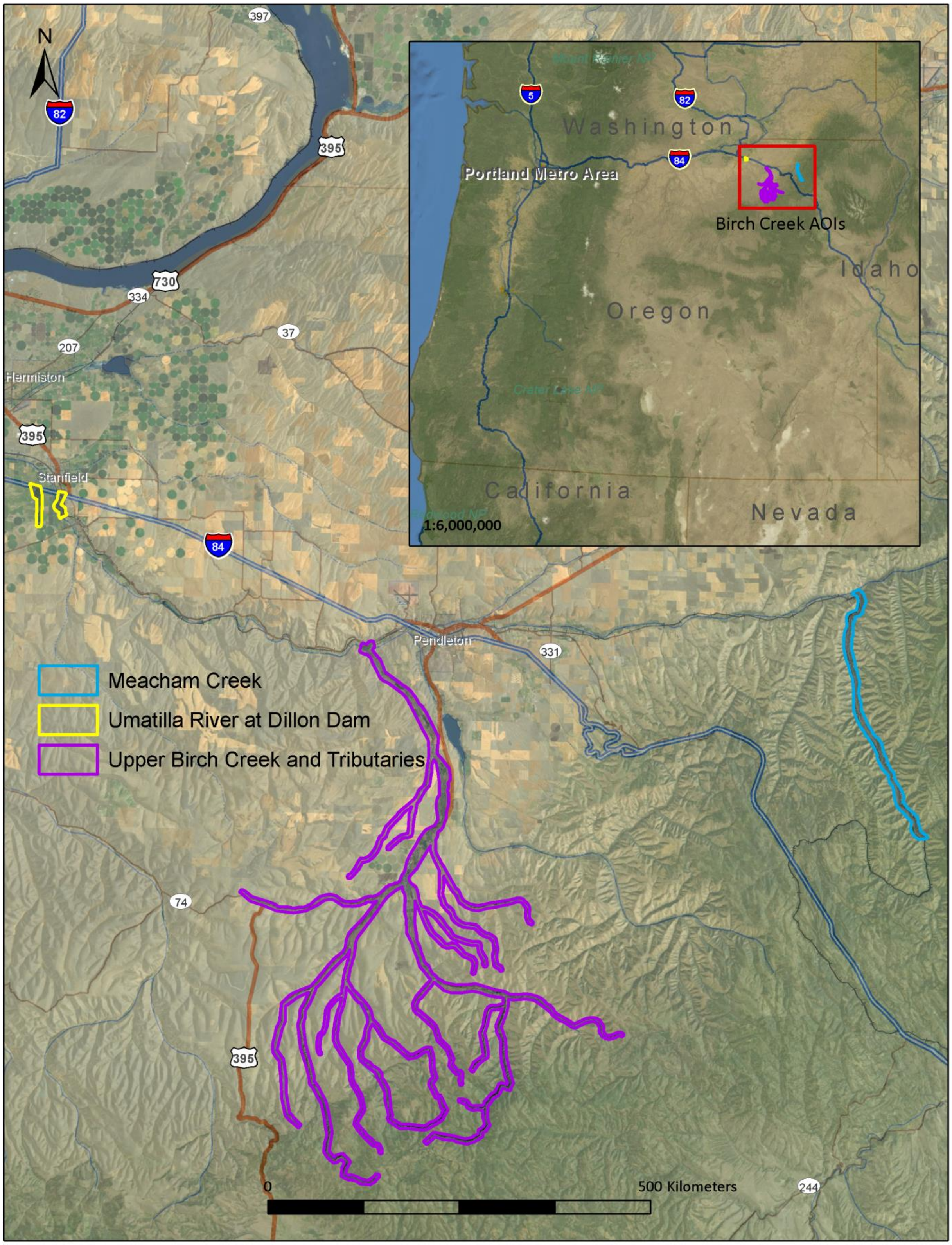


Figure 1: Location map of the Birch Creek Streams sites in Oregon

Table 2: Products delivered to the Umatilla Basin Watershed Council for the Birch Creek Streams sites

<table>
<tr><th colspan="2">Birch Creek Streams Products
Projection: UTM Zone 11N
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12A)
Units: Meters</th></tr>
<tr><td>LAS Files</td><td>LAS v 1.2
• All Returns
• Ground Points</td></tr>
<tr><td>Rasters</td><td>1.0 Meter ESRI Grids
• Bare Earth Model
• Highest Hit Model
• Ground Density Raster
0.5 Meter GeoTiffs
• Intensity Images</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
• Site Boundary
• LiDAR Index
• DEM/DSM Index
• Orthoimagery Index
Text Files (*.txt)
• Smooth Best Estimate Trajectory (SBETs)</td></tr>
<tr><td>Digital Imagery</td><td>15 cm GSD GeoTiffs
• Imagery Mosaics (RGB)</td></tr>
</table>

WSI Cessna Caravan

Planning

In preparation for data collection, WSI reviewed the project area using Google Earth, and flightlines were developed using a combination of specialized software. Careful planning by acquisition staff entailed adapting the pulse rate, flight altitude, scan angle, and ground speed to ensure complete coverage of the Birch Creek Streams LiDAR study area at the target point density of ≥8 pulses per square meter (0.74 pulses/square foot). Efforts are taken to optimize flight paths by minimizing flight times while meeting all accuracy specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or air quality conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations.

Ground Survey

Ground survey data are used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final LiDAR data. Ground surveys, including monumentation and ground check points, are conducted to support the airborne acquisition process.

Monumentation

The spatial configuration of ground survey monuments provided redundant control within 13 nautical miles of the mission areas for LiDAR flights. Monuments were also used for collection of ground control points using RTK survey techniques (see **RTK** below).

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for RTK coverage. WSI established 2 new monuments and utilized 6 existing monuments for the Birch Creek Streams project (Table 3, Figure 2). New monumentation was set using 5/8”x30” rebar topped with stamped 2" aluminum caps. WSI’s professional land surveyor, Chris Yotter-Brown (ORPLS#60438LS) oversaw and certified the establishment of all monuments.

Table 3: Monuments established for the Birch Creek Streams acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
BRCH_CRK_01	45° 25' 20.81937"	-118° 53' 27.13293"	608.085
BRCH_CRK_02	45° 26' 19.52281"	-118° 47' 56.23275"	643.694
ME_RI_01	45° 42' 13.00359"	-118° 21' 20.31851"	520.012
ODOT_N24	45° 45' 18.60021"	-119° 12' 06.11734"	213.008
RB0343	45° 34' 07.38357"	-118° 47' 21.19390"	423.571
RB1372	45° 35' 45.86210"	-118° 48' 06.94132"	412.970
RB1489	45° 08' 15.86618"	118° 57' 27.86513"	992.593
UMT_TIR_05	45° 41' 19.18229"	-118° 51' 06.11866"	431.270

To correct the continuous onboard measurements of the aircraft position recorded throughout the missions, WSI concurrently conducted multiple static Global Navigation Satellite System (GNSS) ground surveys (1 Hz recording frequency) over each monument. After the airborne survey, the static GPS data were triangulated with nearby Continuously Operating Reference Stations (CORS) using the Online Positioning User Service (OPUS[1]) for precise positioning. Multiple independent sessions over the same monument were processed to confirm antenna height measurements and to refine position accuracy.

[1] OPUS is a free service provided by the National Geodetic Survey to process corrected monument positions. http://www.ngs.noaa.gov/OPUS.

Monuments were established according to the national standard for geodetic control networks, as specified in the Federal Geographic Data Committee (FGDC) Geospatial Positioning Accuracy Standards for geodetic networks.[2] This standard provides guidelines for classification of monument quality at the 95% confidence interval as a basis for comparing the quality of one control network to another. The monument rating for this project can be seen in Table 4.

Table 4: Federal Geographic Data Committee monument rating

Direction	Rating
St Dev $_{NE}$:	0.050 m
St Dev $_{z}$:	0.050 m

For the Birch Creek Streams project, the monument positions contributed no more than 5 cm of horizontal and vertical error to the final RTK and LiDAR positions, with 95% confidence.

RTK Surveys

For the real time kinematic (RTK) check point data collection, a Trimble R7 base unit was positioned at a nearby monument to broadcast a kinematic correction to a roving Trimble R8 GNSS receiver. All RTK measurements were made during periods with a Position Dilution of Precision (PDOP) of ≤ 3.0 with at least six satellites in view of the stationary and roving receivers. When collecting RTK data, the rover would record data while stationary for five seconds, then calculate the pseudorange position using at least three one-second epochs. Relative errors for the position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. See Table 5 for Trimble unit specifications.

RTK positions were collected on paved roads and other hard surface locations such as gravel or stable dirt roads that also had good satellite visibility. RTK measurements were not taken on highly reflective surfaces such as center line stripes or lane markings on roads due to the increased noise seen in the laser returns over these surfaces. The distribution of RTK points depended on ground access constraints and may not be equitably distributed throughout the study area. See Figure 2 for the distribution of RTK in this project.

[2] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.2-1998). Part 2: Standards for Geodetic Networks, Table 2.1, page 2-3. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part2/chapter2

Table 5: Trimble equipment identification

Receiver Model	Antenna	Example	OPUS Antenna ID	Use
Trimble R7 GNSS	Zephyr GNSS Geodetic Model 2		TRM57971.00	Static
Trimble R8	Integrated Antenna R8 Model 2		TRM_R8_GNSS	RTK

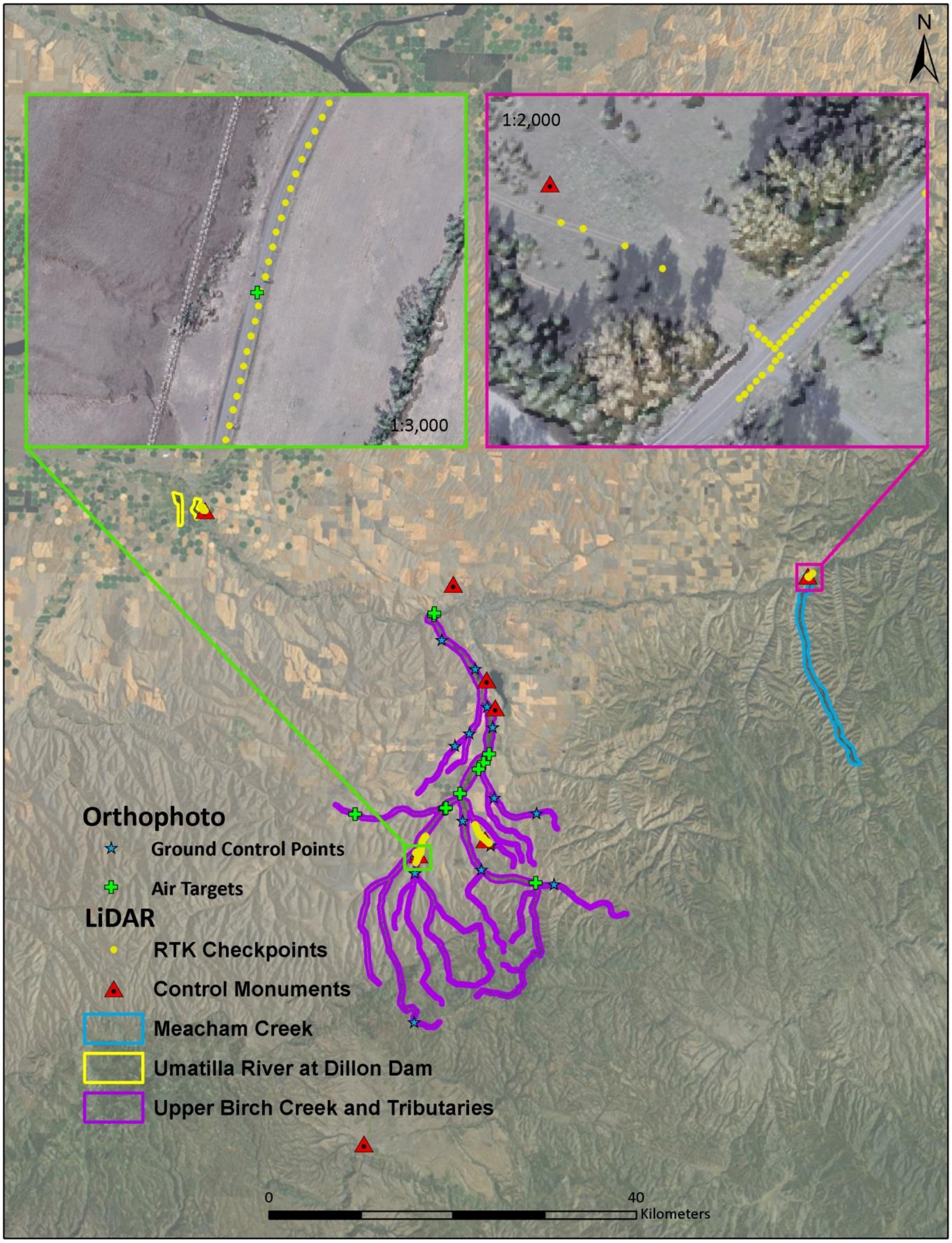


Figure 2: Basestation, Air Target and RTK checkpoint location map

Airborne Survey

LiDAR

The LiDAR survey was accomplished with a Leica ALS70 system mounted in a Cessna Caravan. Table 6 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Birch Creek Streams terrain. It is not uncommon for some types of surfaces (e.g. dense vegetation or water) to return fewer pulses to the LiDAR sensor 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.

Table 6: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Sensor	Leica ALS70
Survey Altitude (AGL)	1,200 m
Target Pulse Rate	201-226 kHz
Sensor Configuration	Single Pulse in Air (SPiA)
Laser Pulse Diameter	28 cm
Field of View	30^o
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	4
Intensity	8-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS70 LiDAR sensor

To reduce laser shadowing and increase surface laser painting, all areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap). The Leica laser systems record up to four range measurements (returns) per pulse. All discernible laser returns were processed for the output dataset.

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. Position of the aircraft 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.

Digital Imagery

The aerial imagery was collected using a Vexcel UltraCam XP camera (Table 7) by 3Di (Eugene, Oregon). The Vexcel is a large format digital aerial camera manufactured by Microsoft Corporation. The system is gyro-stabilized and simultaneously collects panchromatic and multispectral (RGB, NIR) imagery. Panchromatic lenses collect high resolution imagery by illuminating 9 charge coupled device (CCD) arrays, writing 9 raw image files. RGB and NIR lenses collect lower resolution imagery, written as 4 individual raw image files. Level 2 images are created by stitching together raw image data from the 9 panchromatic CCDs and are ultimately combined with the multispectral image data to yield Level 3 pan-sharpened TIFFs.

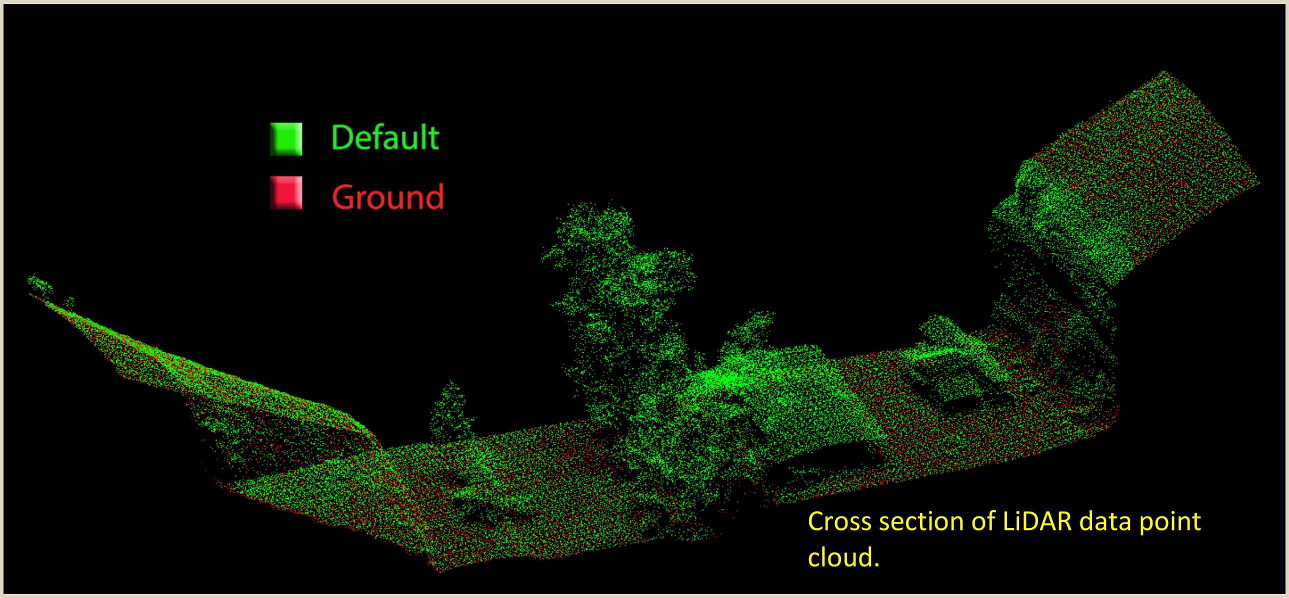
Table 7: Camera manufacturer's specifications

UltraCam XP	
Focal Length	100.5 mm
Data Format	RGB NIR
Pixel Size	6.0 µm
Image Size	17,310 x 11,310 pixels
Frame Rate	2 seconds
FOV	66° x 46°

For the Birch Creek Streams site, images were collected in 4 spectral bands (red, green, blue, and NIR) with 60% along track overlap and 30% sidelap between frames. The acquisition flight parameters were designed to yield a native pixel resolution of ≤ 15cm, which exceeds the minimum requested orthophoto scale of 6 inches (or 15.24cm). The resulting spatial accuracies (RMSE) were routinely ≤ 45cm at 95% confidence level. Orthophoto specifications particular to the Birch Creek Streams project are in Table 8.

Table 8: Project-specific orthophoto specifications

Digital Orthophotography Specifications	
Equipment	UltraCam XP
Spectral Bands	Red, Green, Blue, NIR
Resolution	15 cm pixel size
Along Track Overlap	≥60%
Flight Altitude MSL)	2,200 meters
GPS Baselines	≤25 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Horizontal Accuracy	0.06 m
Image	8-bit GeoTiff



Cross section of LiDAR data point cloud.

LiDAR Data

Upon the LiDAR data's arrival to the office, WSI processing staff initiates a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks include GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, calibration for optimal relative and absolute accuracy, and classification of ground and non-ground points (Table 9). Processing methodologies were tailored for the riparian habitat of the Umatilla Basin Watershed and intended application of habitat restoration and water quality analysis of the point data. A full description of these tasks can be found in Table 10.

Table 9: ASPRS LAS classification standards applied to the Birch Creek Streams dataset

Classification Number	Classification Name	Classification Description
1	Default/ Unclassified	Laser returns that are not included in the ground class and not dismissed as Noise or Withheld points
2	Ground	Ground that is determined by a number of automated and manual cleaning algorithms to determine the best ground model the data can support

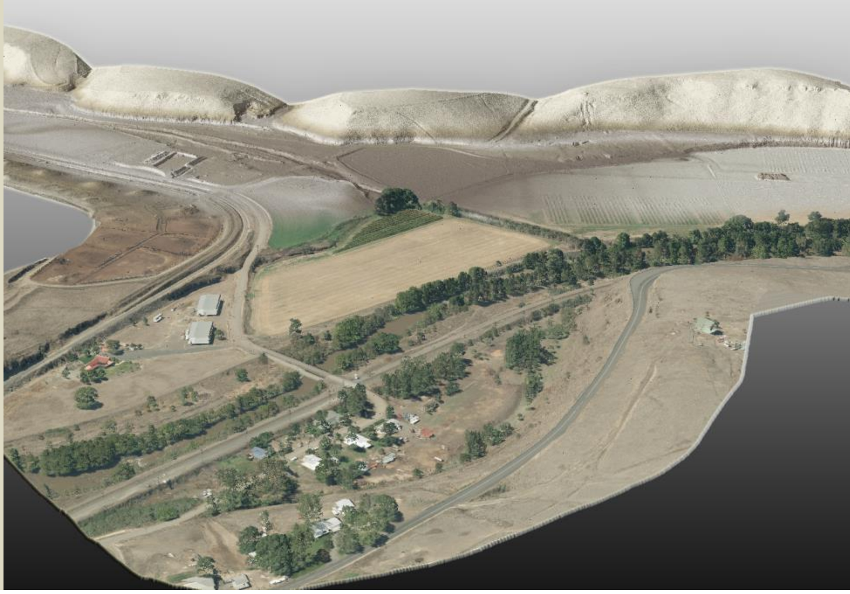
Table 10: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.	Waypoint GPS v.8.3 Trimble Business Center v.3.00 Geographic Calculator 2013
Develop a smoothed best estimate of trajectory (SBET) file that blends 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.	IPAS TC v.3.1
Calculate laser point position by associating 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 v. 1.2) format. Data are converted to orthometric elevations (NAVD88) by applying a Geoid12 correction.	ALS Post Processing Software v.2.74
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).	TerraScan v.13.008
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 calculated on ground classified points from paired flight lines and results are applied to all points in a flight line. Every flight line is used for relative accuracy calibration.	TerraMatch v.13.002
Classify resulting data to ground and other client designated ASPRS classifications (Table 9). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground RTK survey data.	TerraScan v.13.008 TerraModeler v.13.002
Generate bare earth models as triangulated surfaces. Highest hit models were created as a surface expression of all classified points (excluding the noise and withheld classes). All surface models were exported as ESRI Grids at a 1 meter pixel resolution.	TerraScan v.13.008 ArcMap v. 10.1 TerraModeler v.13.002

Digital Imagery

WSI in collaboration with 3Di (Eugene, Oregon) acquired 4-band digital imagery of the Birch Creek Streams sites. Individual image frames were combined into one seamless mosaic, then subset into tiles to make the file size more manageable. Intensity images were used to identify checkpoints on the ground the measure accuracy and ensure co-registration with the LiDAR.

View of the Umatilla River just outside of Pendleton. The forefront is the gridded-bare earth model and vegetation LiDAR point cloud draped with 15cm orthoimagery, the background is the bare-earth model colored by elevation.



LiDAR Density

The sensor is set to acquire a native density of 8 points/m^2. Depending on the nature of the terrain, the first returned echo will be the highest hit surface. In vegetated areas, the first return surface will represent the top of the canopy, while in clearings or on paved roads, the first return surface will represent the ground. The ground density differs from the first return density due to the fact that in vegetated areas, fewer returns may penetrate the canopy. The ground classification is generally determined by first echo returns in non-vegetated areas combined with last echo returns in vegetated areas. The pulse density distribution will vary within the study area due to laser scan pattern and flight conditions. Additionally, some types of surfaces (i.e. breaks in terrain, water, steep slopes) may return fewer pulses to the sensor than originally emitted by the laser.

The cumulative average first-return density for the LiDAR data for the Birch Creek Streams was 18.418 points/m^2 (1.711 points/ft^2) while the cumulative average ground classified density was 7.670 points/m^2 (0.713 points/ft^2) (Table 11). The statistical distribution of first returns (Figure 3) and classified ground points (Figure 4) are portrayed below. Also presented are the spatial distribution of average first return densities (Figure 5) and ground point densities (Figure 6) for each 100mx100m cell.

Table 11: Average LiDAR point densities

Classification	Point Density			
AOI	**Cumulative**	**Birch Creek**	**Meacham Creek**	**Dillon Dam**
First-Return	18.418 points/m^2	18.621 points/m^2	18.675 points/m^2	14.503 points/m^2
Ground Classified	7.670 points/m^2	7.986 points/m^2	5.250 points/m^2	6.924 points/m^2

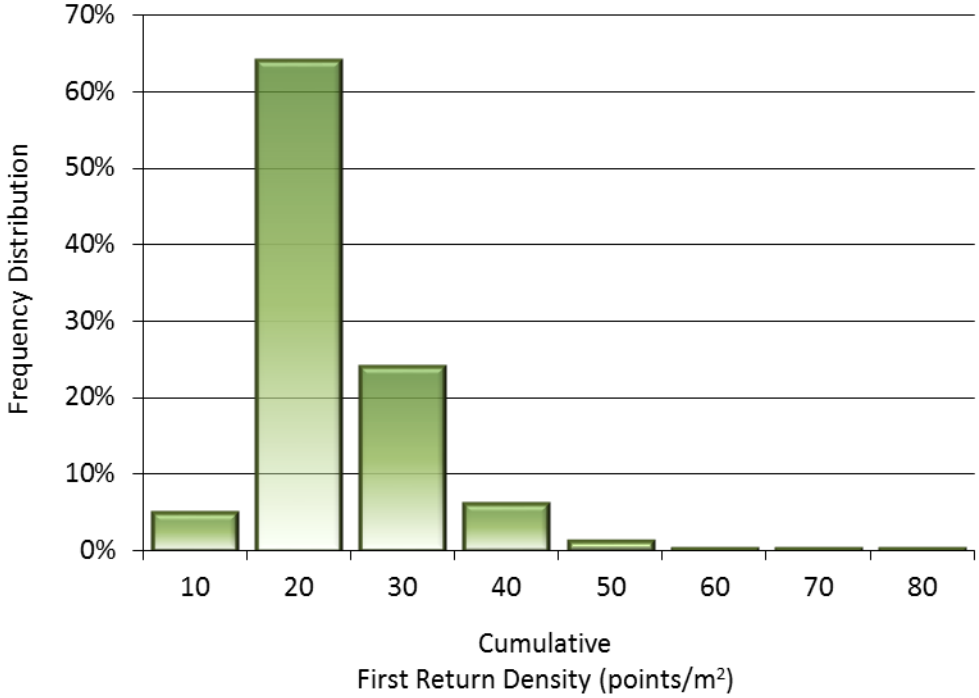


Figure 3: Frequency distribution of first return densities (native densities) of the gridded study area

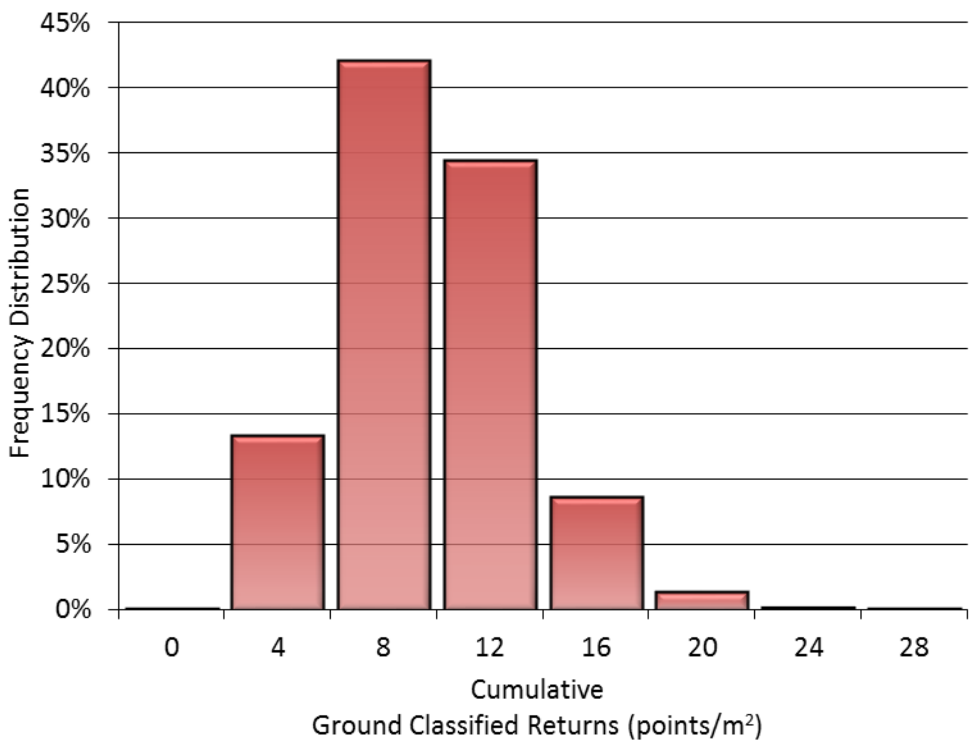


Figure 4: Frequency distribution of ground return densities of the gridded study area

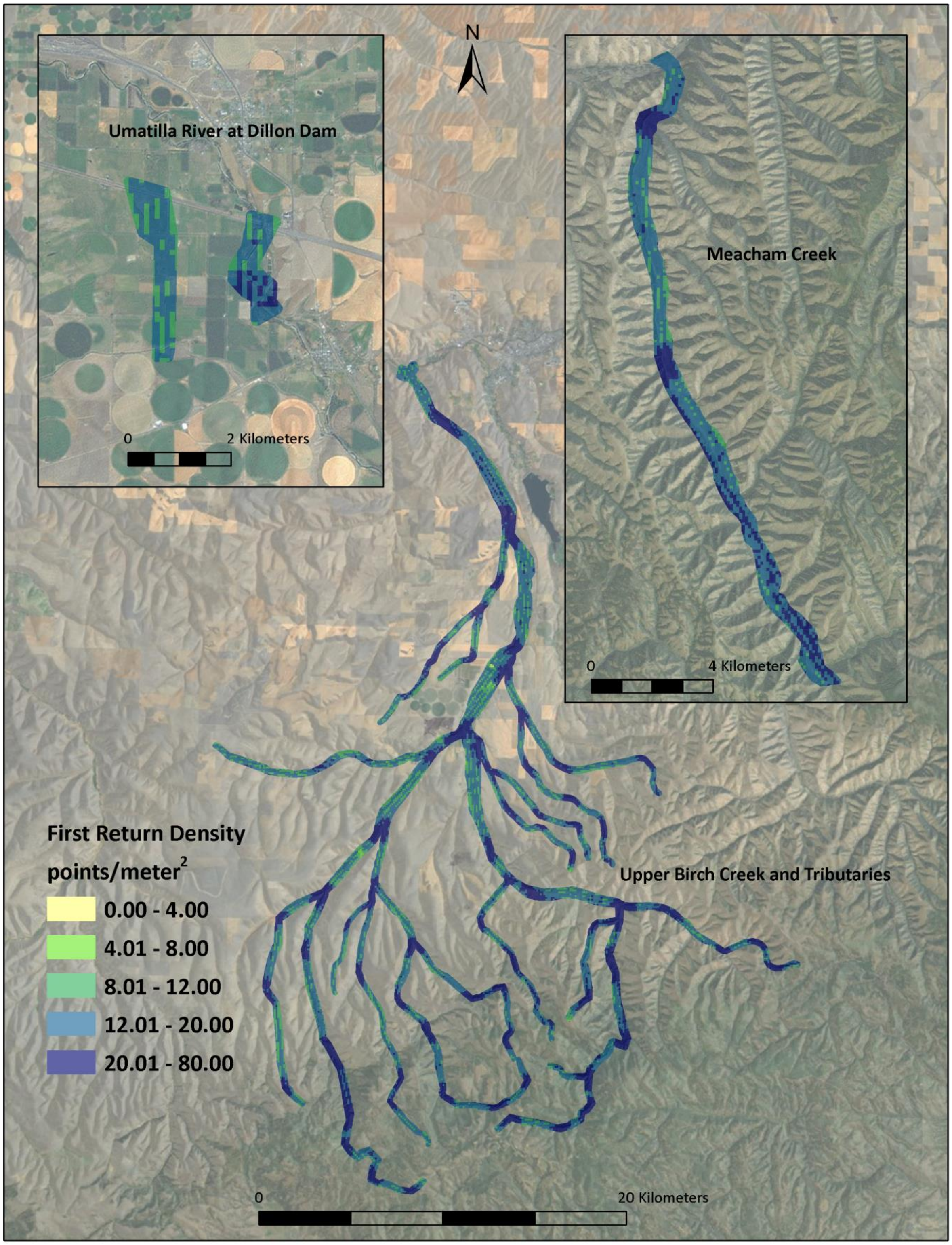


Figure 5: Native density map for the Birch Creek Streams sites (100mx100m cells)

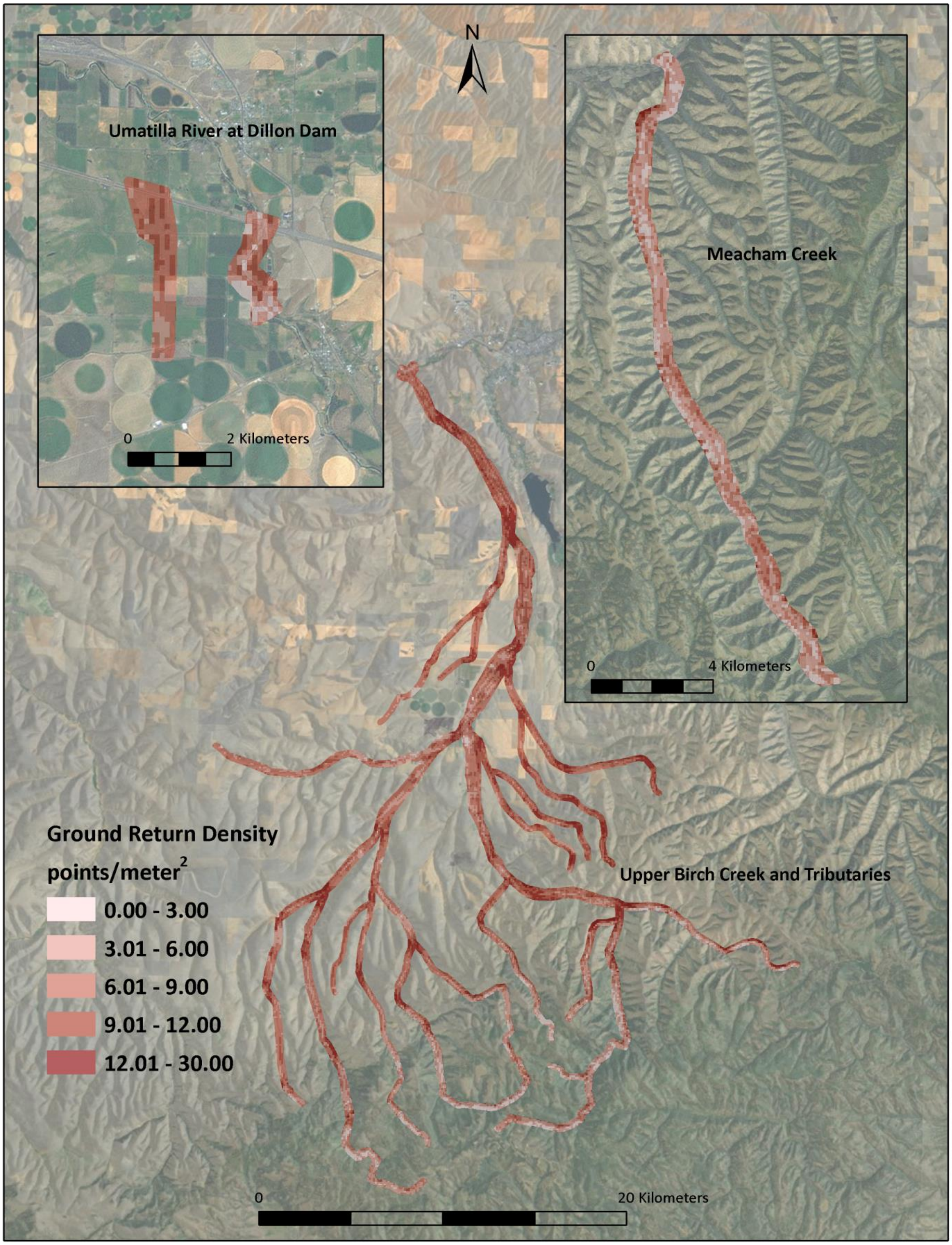


Figure 6: Ground density map for the Birch Creek Streams sites (100mx100m cells)

LiDAR Accuracy Assessments

The accuracy of the LiDAR data collection can be described in terms of absolute accuracy (the consistency of the data with external data sources) and relative accuracy (the consistency of the dataset with itself). See Appendix A for further information on sources of error and operational measures used to improve relative accuracy.

LiDAR Absolute Accuracy

Vertical absolute accuracy was primarily assessed from RTK ground check point (GCP) data collected on open, bare earth surfaces with level slope (<20°). Fundamental Vertical Accuracy (FVA) reporting is designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. FVA compares known RTK ground survey check points to the triangulated ground surface generated by the LiDAR points. FVA is a measure of the accuracy of LiDAR point data in open areas where the LiDAR system has a "very high probability" of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 σ).

Absolute accuracy is described as the mean and standard deviation (sigma σ) of divergence of the ground surface model from ground survey point coordinates. These statistics assume the error for x, y, and z is normally distributed, and therefore the skew and kurtosis of distributions are also considered when evaluating error statistics. For the Birch Creek Streams survey, 1,014 points were collected in total resulting in an average accuracy of -0.003 meters (Table 12, Figure 7).

Table 12: Absolute accuracy

	Cumulative	Birch Creek	Meacham Creek	Dillon Dam
Sample	1,014 points	757 points	98 points	159 points
Average	-0.003 m	-0.005 m	-0.001 m	0.003 m
Median	-0.002 m	-0.003 m	0.000 m	0.002 m
RMSE	0.026 m	0.026 m	0.023 m	0.028 m
Standard Deviation (1σ)	0.026 m	0.026 m	0.024 m	0.027 m
1.96σ	0.051 m	0.050 m	0.046 m	0.054 m

[3] Federal Geographic Data Committee, Geospatial Positioning Accuracy Standards (FGDC-STD-007.3-1998). Part 3: National Standard for Spatial Data Accuracy. http://www.fgdc.gov/standards/projects/FGDC-standards-projects/accuracy/part3/chapter3

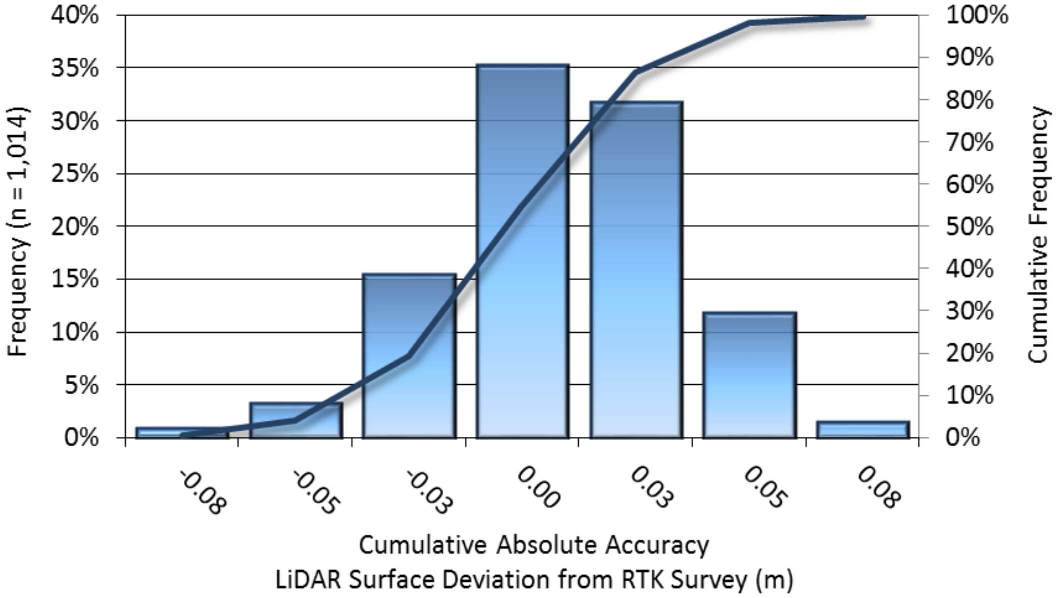


Figure 7: Cumulative frequency histogram for LiDAR surface deviation from RTK values

LiDAR Vertical Relative Accuracy

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the LiDAR system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy is computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The cumulative average (mean) line to line relative vertical accuracy for the Birch Creek Streams was 0.035 meters (Table 13, Figure 8).

Table 13: Relative accuracy

	Cumulative	Birch Creek	Meacham Creek	Dillon Dam
Sample	403 surfaces	360 surfaces	31 surfaces	12 surfaces
Average	0.035 m	0.035 m	0.036 m	0.024 m
Median	0.034 m	0.034 m	0.037 m	0.024 m
RMSE	0.035 m	0.035 m	0.035 m	0.024 m
Standard Deviation (1σ)	0.006 m	0.006 m	0.006 m	0.001 m
1.96σ	0.012 m	0.012 m	0.011 m	0.003 m

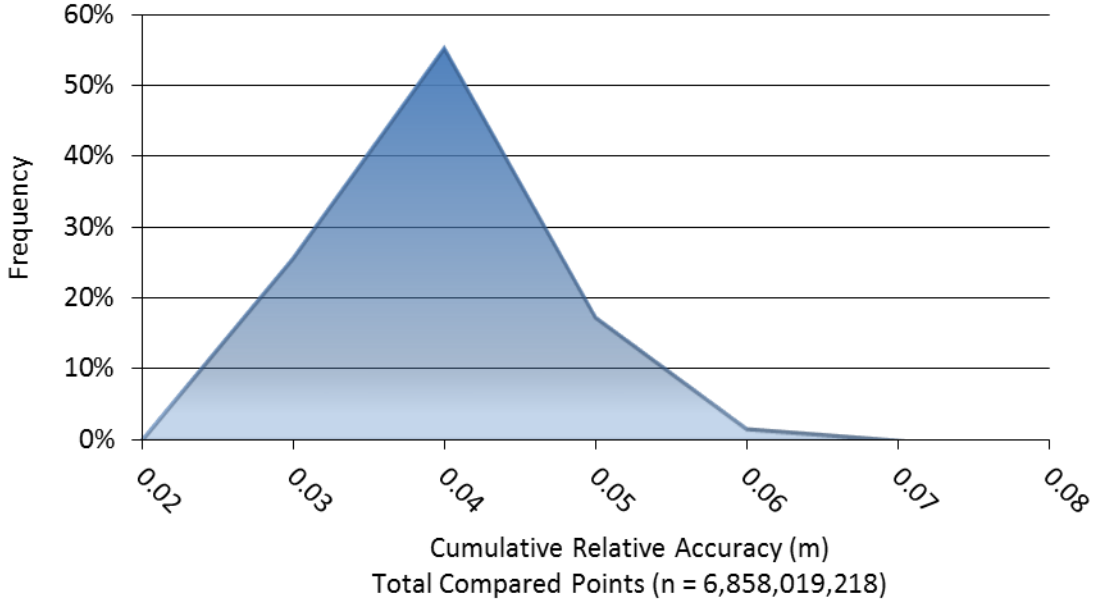


Figure 8: Cumulative frequency plot for relative vertical accuracy between flight lines

Digital Imagery Accuracy Assessment

Image accuracy is measured by both air target locations and independent ground check points. Air target GPS points were measured against the placement of the air target in the imagery. In addition, ground check points were identified on the LiDAR intensity images in areas of clear visibility. Once the ground check points were identified in the intensity images the exact spot was identified in the orthophotography and the displacement was recorded for further statistical analysis (Figure 2).

Table 14 presents the complete photo accuracy statistics, Figure 9 contains a scatterplot showing congruence between LiDAR intensity images and orthophotos in aerial target locations, while Figure 10 shows an example of the co-registration of the orthophotos to the LiDAR intensity images.

Table 14: Orthophotography accuracy statistics for Birch Creek Streams

Birch Creek Streams Photo Accuracy							
		Check Points$_x$	Check Points$_y$	Check Points$_{xy}$	Air Targets$_x$	Air Targets$_y$	Air Targets$_{xy}$
Count		14			11		
Mean	*ft*	-0.069	0.062	0.095	0.000	0.066	0.066
	m	-0.021	-0.019	0.029	0.000	0.020	0.020
RMSE	*ft*	0.308	0.265	0.407	0.069	0.177	0.190
	m	0.094	0.081	0.124	0.021	0.054	0.058
1σ	*ft*	0.315	0.269	0.413	0.049	0.075	0.092
	m	0.096	0.082	0.126	0.015	0.023	0.028
1.96σ	*ft*	0.614	0.525	0.807	0.095	0.148	0.180
	m	0.187	0.160	0.246	0.029	0.045	0.055

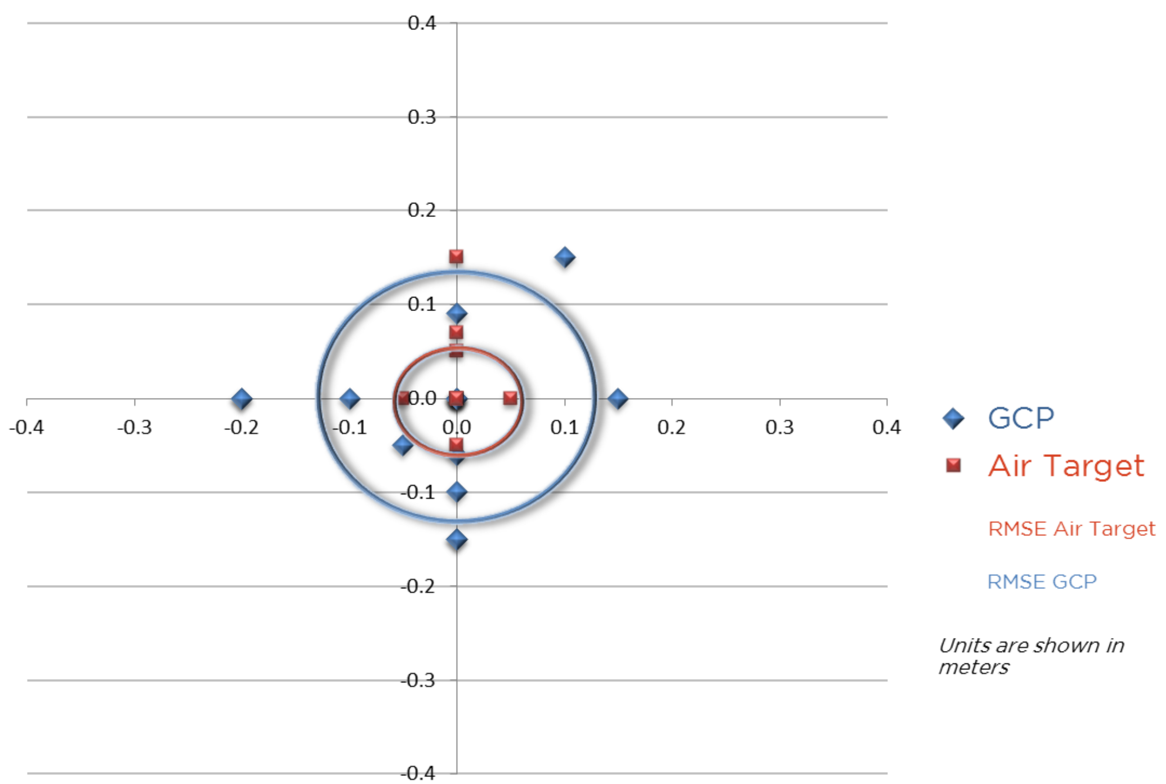


Figure 9: Scatterplot displaying the XY deviation of aerial targets aligned with the orthophoto imagery when compared against the LiDAR intensity images.

Figure 10: Image displaying the co-registration between the LiDAR intensity image and the orthophoto at a location within the Birch Creek Streams site.

Watershed Sciences provided LiDAR services for the Birch Creek Streams project as described in this report.

I, Russ Faux, have reviewed the attached report for completeness and hereby state that it is a complete and accurate report of this project.

Russ Faux
Principal
WSI

I, Christopher W. Yotter-Brown, being first duly sworn, say that as described in the Ground Survey subsection of the Acquisition section of this report was completed by me or under my direct supervision and was completed using commonly accepted standard practices. Accuracy statistics shown in the Accuracy Section have been reviewed by me to meet National Standard for Spatial Data Accuracy.

REGISTERED PROFESSIONAL LAND SURVEYOR

11/4/2013

OREGON
JULY 13, 2004
Christopher W. Yotter - Brown
60438 LS

RENEWAL DATE: 6/30/2014

Christopher W. Yotter-Brown, PLS Oregon & Washington
WSI
Portland, OR 97204

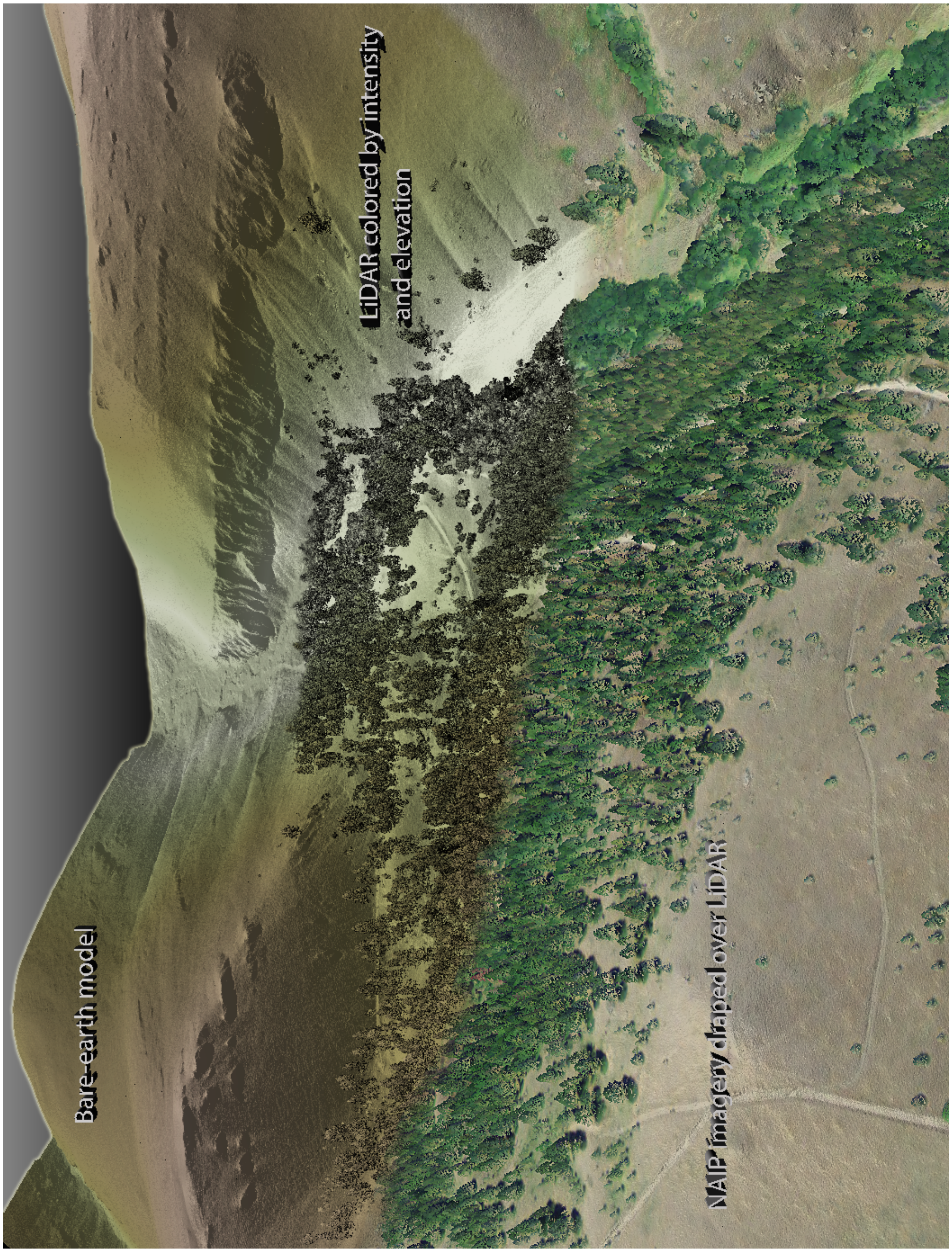


Figure 11: View of Bear Creek along Arlie Canyon. From front to back the image consists of the gridded bare-earth model and vegetation LiDAR point cloud draped with NAIP imagery, the same models colored by intensity and elevation, the bare-earth model alone colored by elevation.

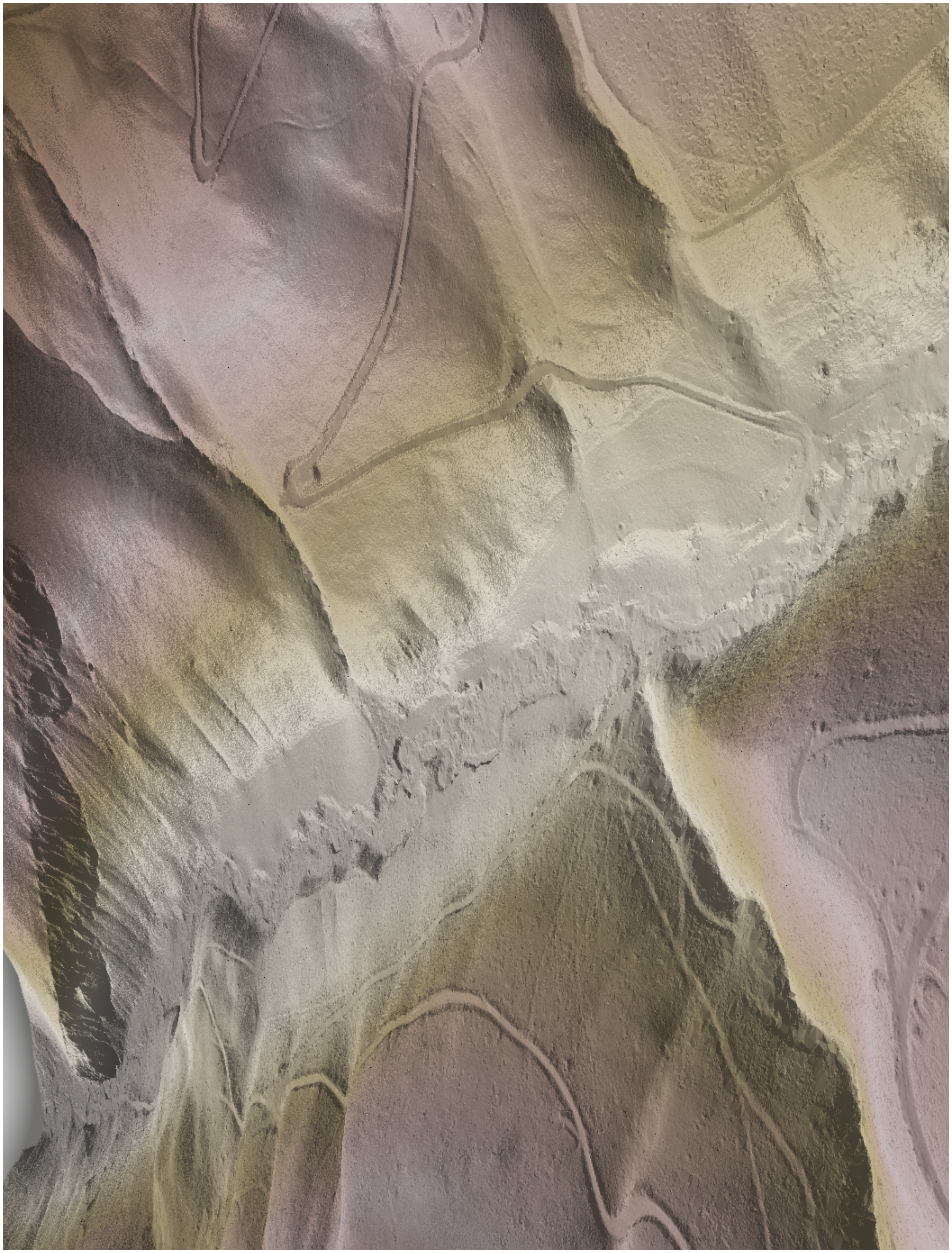


Figure 12: Overhead view of Bear Creek. The gridded bare-earth image is colored by elevation.

Figure 13: View of the intersection of Umatilla River and Birch Creek. The bare-earth gridded model and vegetation point cloud are draped with 15cm orthoimagery.

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 95th percentile) of a normally distributed data set.

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).

> **Absolute Accuracy:** The vertical accuracy of 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.
>
> **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).
>
> **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.

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

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.

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

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.

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.

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

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 60 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.

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.

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

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

Relative Accuracy Calibration Methodology:

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 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.

Automated Attitude Calibration: 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.

Automated Z Calibration: Ground points per line were used to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration was the final step employed for relative accuracy calibration.

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 ±15^{o} 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.

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.

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.

Aerial Triangulation REPORT

Job #:	13-171	Job Name:	Birch Creek			Date:	9-Oct-13
# of Flight Lines:	52	# of Exposures:	693				Color
Aerial Photography by:	Bergman Photographics						
Camera Type:	Vexcel UltraCam XP			Serial #:	10411033		
Focal Length:	100.5000	Pixel size:	6.0	microns		Flown on:	13-Sep-13
Planned Ground Sample Distance (GSD):		14.000	cm	0.140	meters		
Computed Photo Scale:	1:23708	Computed median GSD:		14.225	cm	0.142	meters
Ground Control by:	varied sources*					Number of points:	59
Horizontal Datum:	NAD 83(HARN)			Vertical Datum:	NAVD 88		
Epoch:		Geoid:		Benchmark:			
Coordinate System:	UTM			Zone:	11N		
Units:	meters			Projection:	Transverse Mercator		
AGPS by:	Orbitech, Inc.						

ANALYSIS

Standard Deviation settings used:

Auto image points:	0.002	Image points:	0.002	Control (H):	0.03	Control (V):	0.10
ABGPS (XYZ):	0.1	0.1	0.1				

Redundancy:

# of observations:	460305	redundancy:	310029	redundancy factor:	0.67

Sigma Naught achieved :	0.800	microns	0.100	pixels	0.014	meters

PRECISION *(Root Mean Square Values of Residuals)*:

	# of readings:	X:	Y:	XY:	Z:
Automatic Points (microns):	223973	0.600	0.600	*0.849*	
Manual Points (microns):	4016	0.800	0.800	*1.131*	
Control Points (meters):	59	0.047	0.044	*0.064*	*0.078*
ABGPS (meters):	693	0.060	0.058	*0.083*	*0.036*

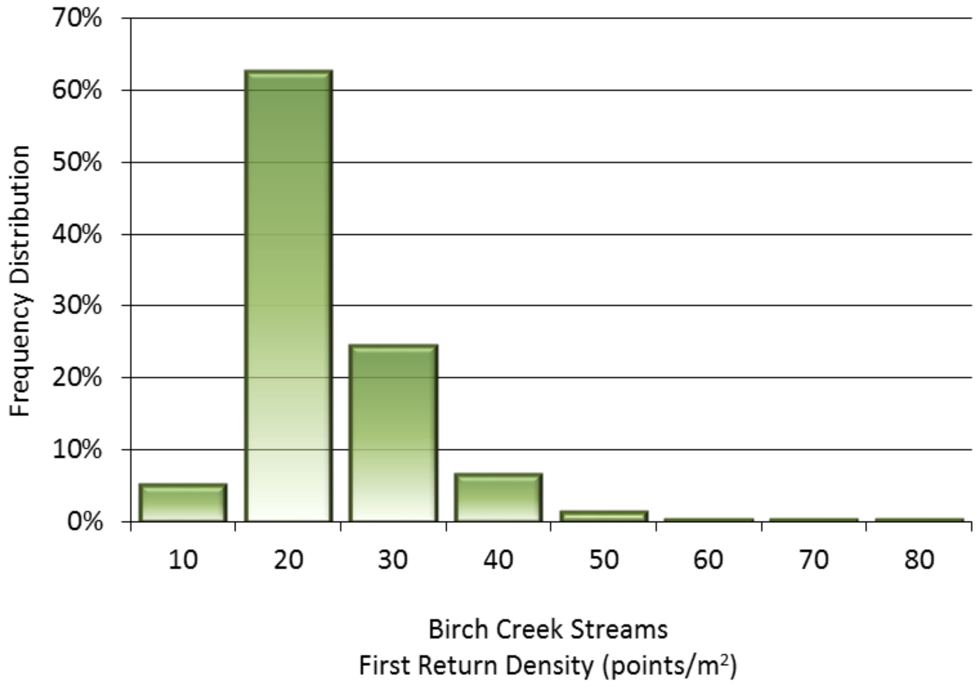
ACCURACY (all values below, except percentages, in meters):

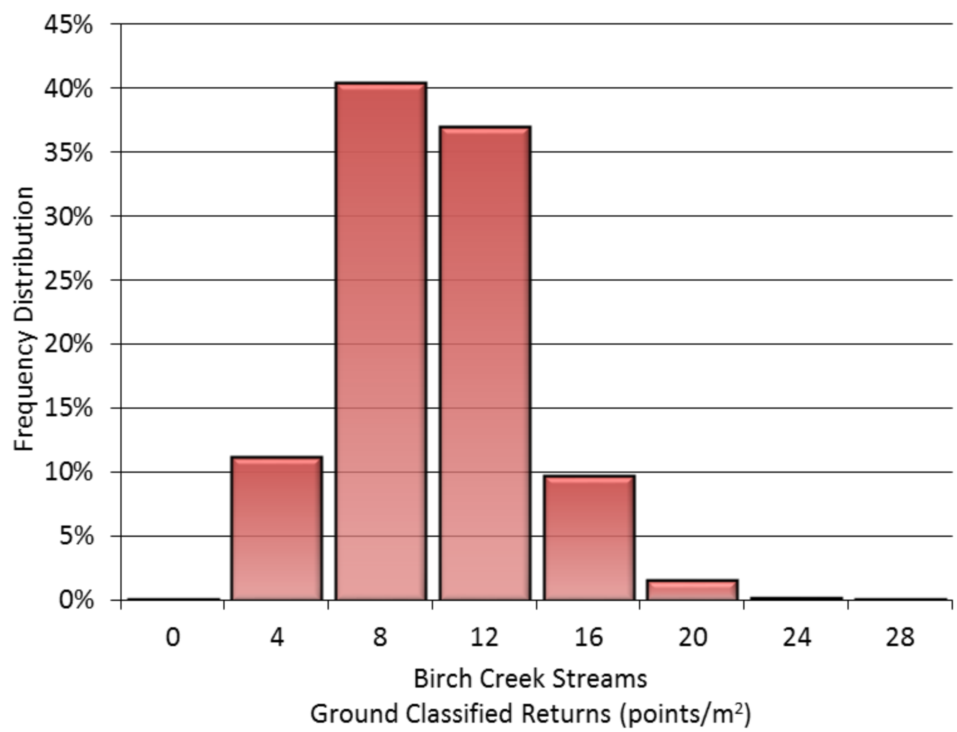
Mean value of standard deviation from adjustment:	X:	0.018	Y:	0.017	H:	*0.025*	V:	*0.049*

COMMENTS

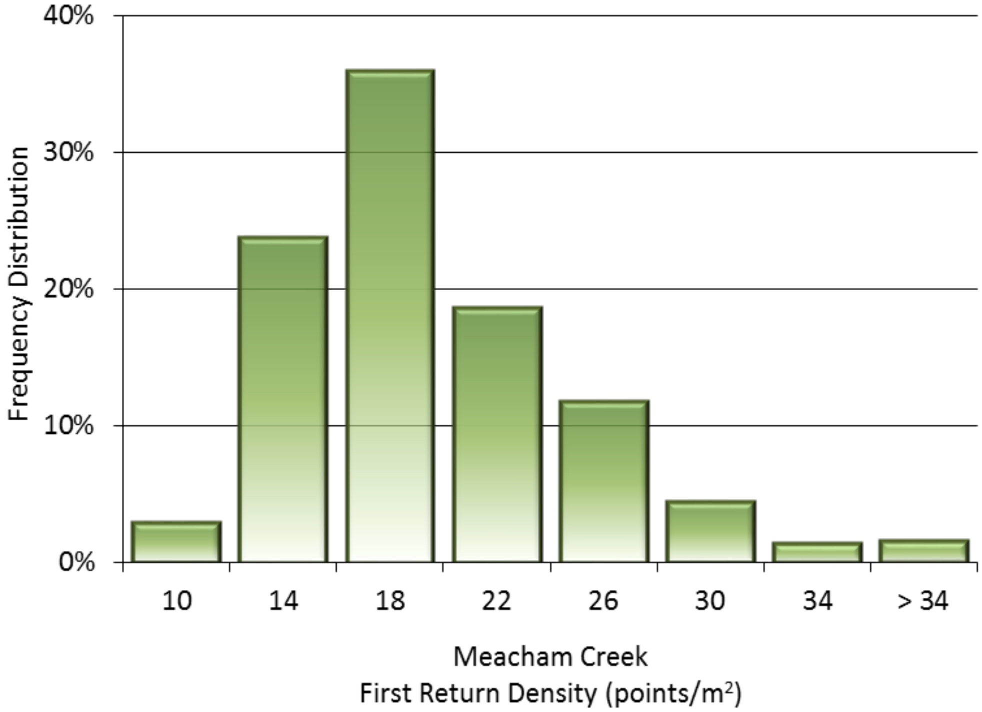
** some from WSI, some derived from LIDAR*

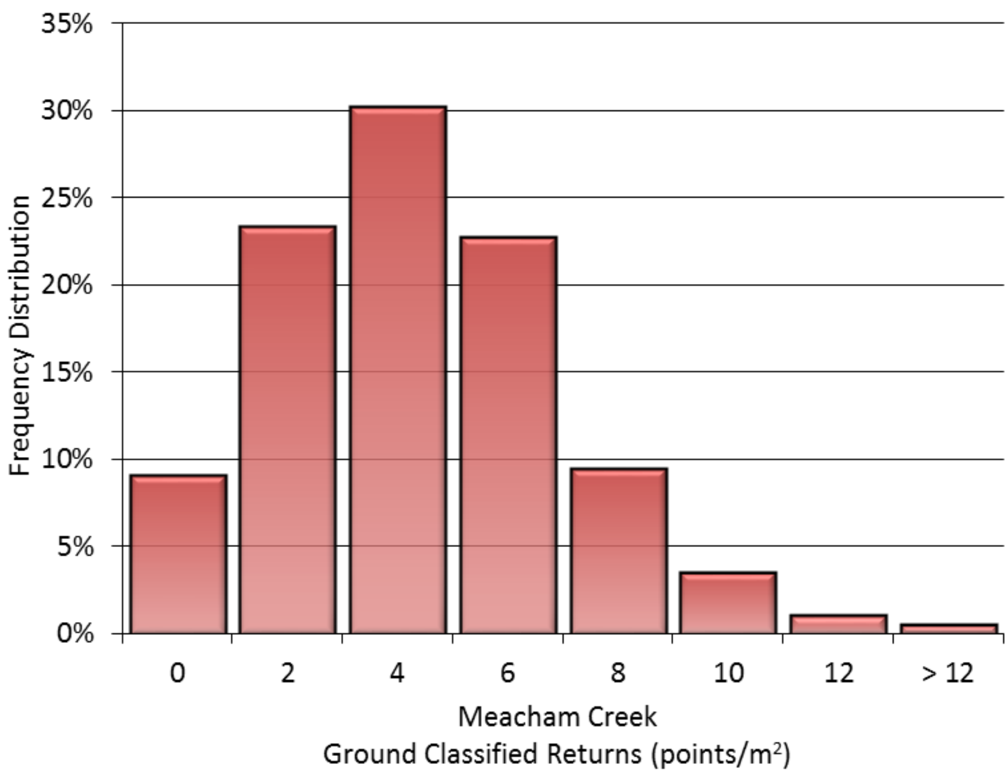
Birch Creek Streams Point Density Frequency Distributions



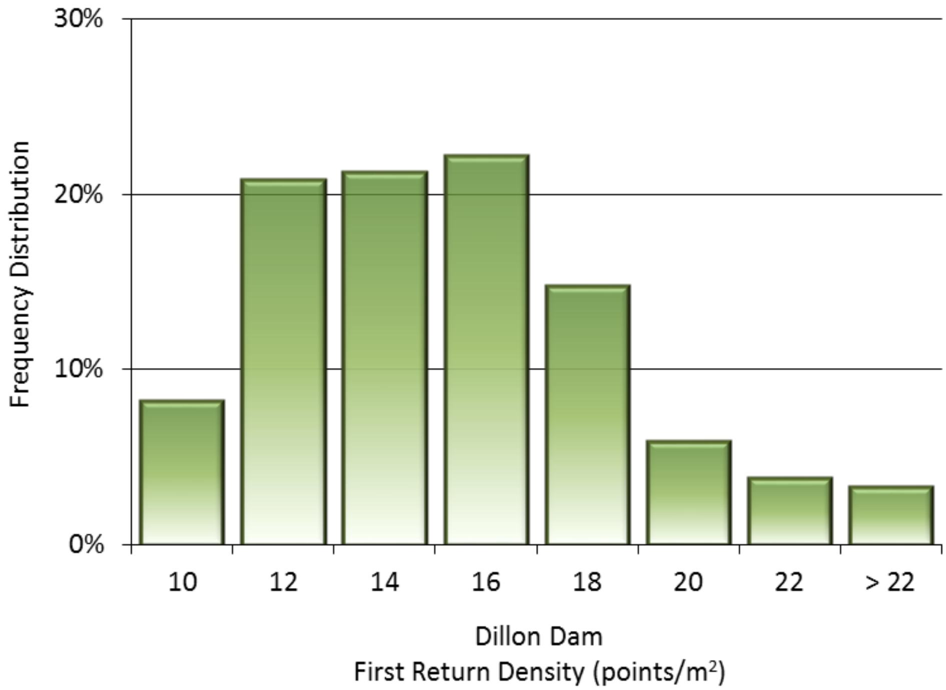


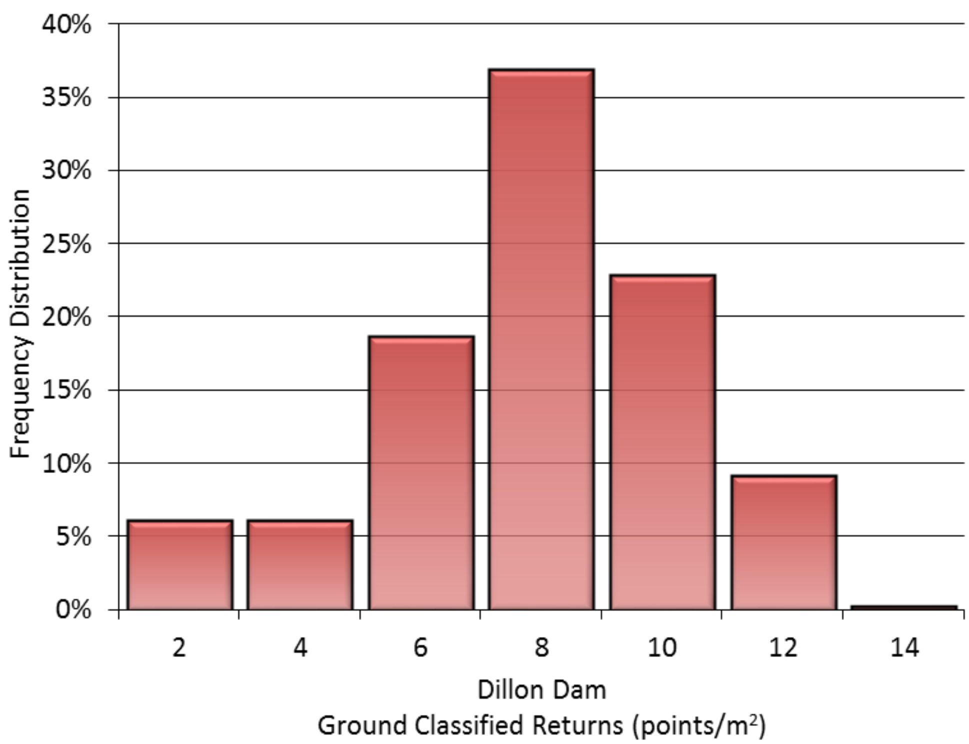
<u>Meacham Creek Point Density Frequency Distributions</u>



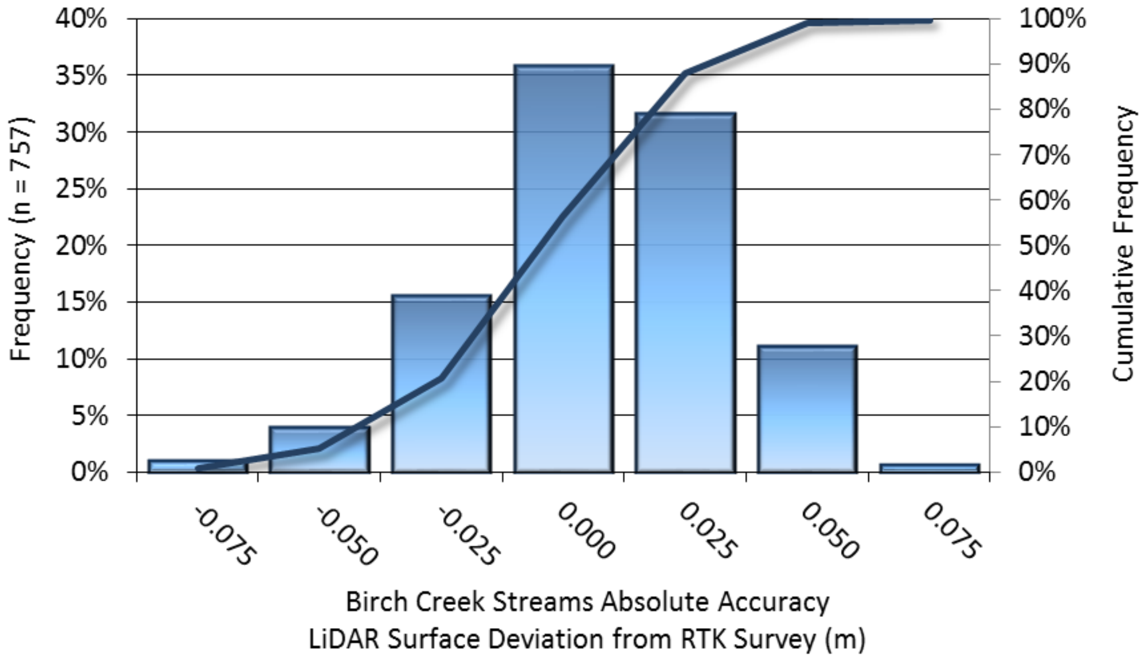


Dillon Dam Point Density Frequency Distributions

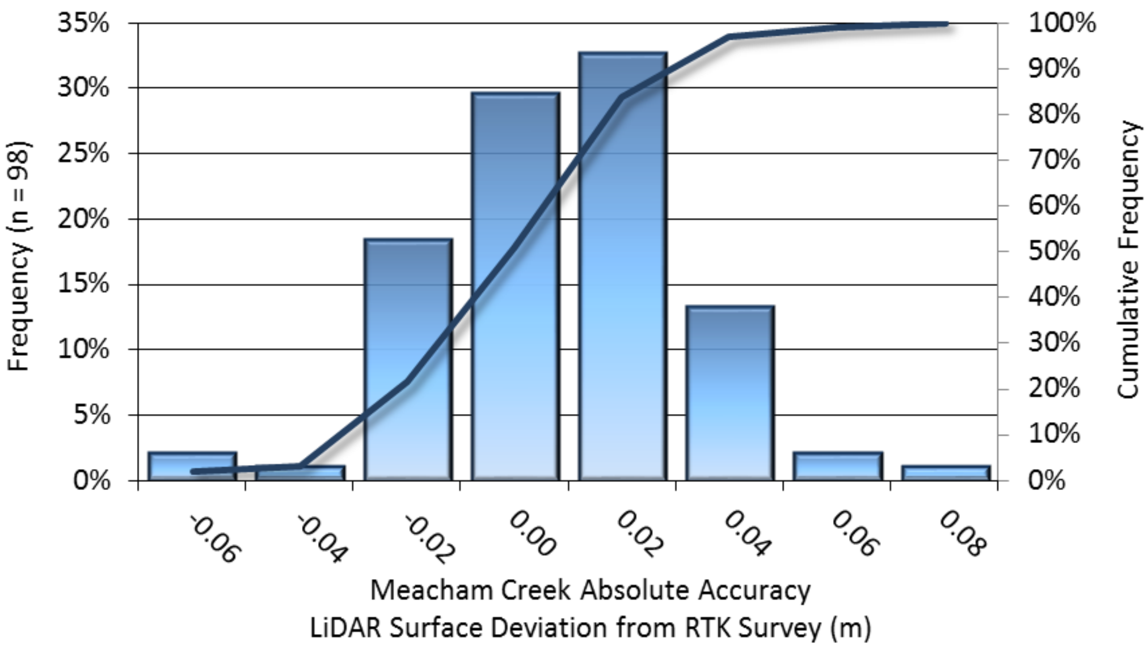




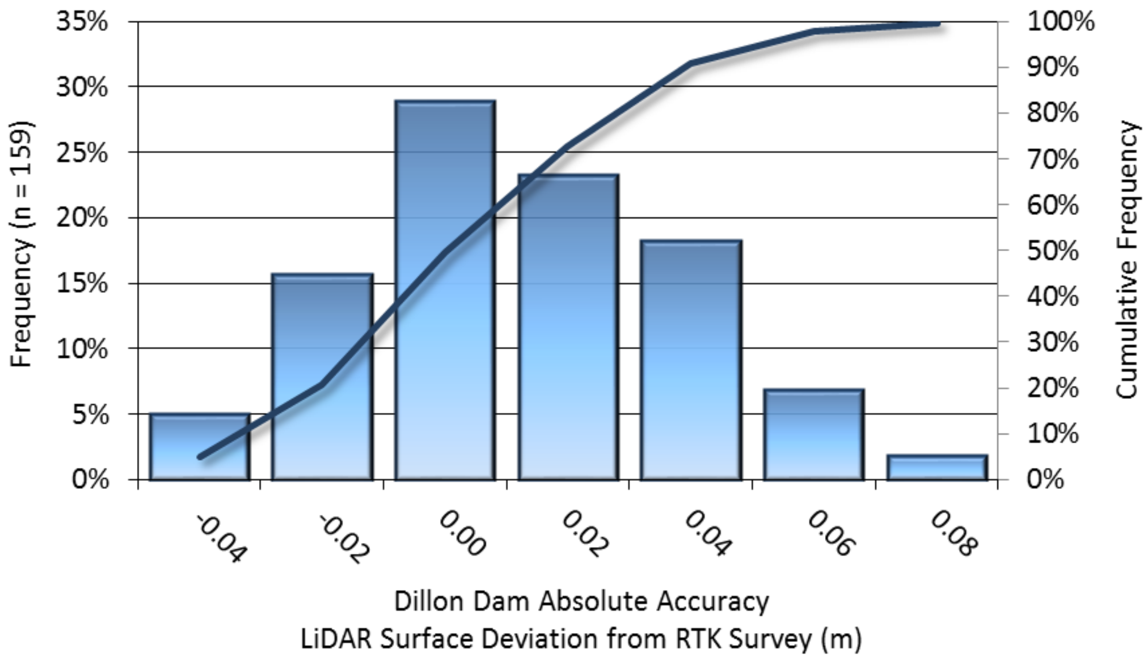
Birch Creek Streams AOI



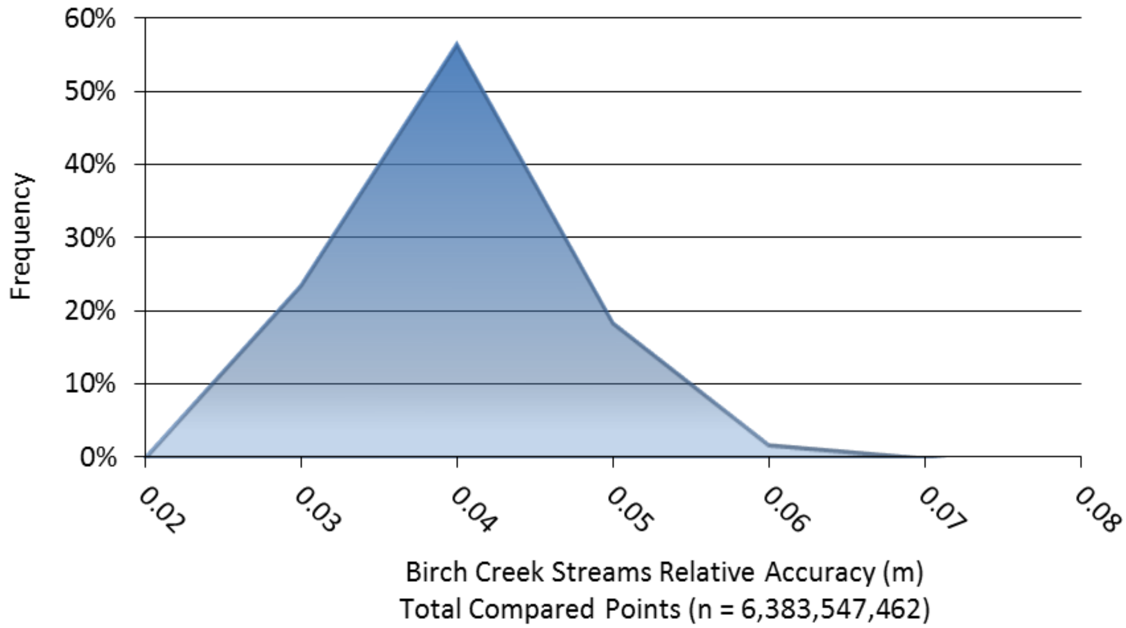
Meacham Creek AOI



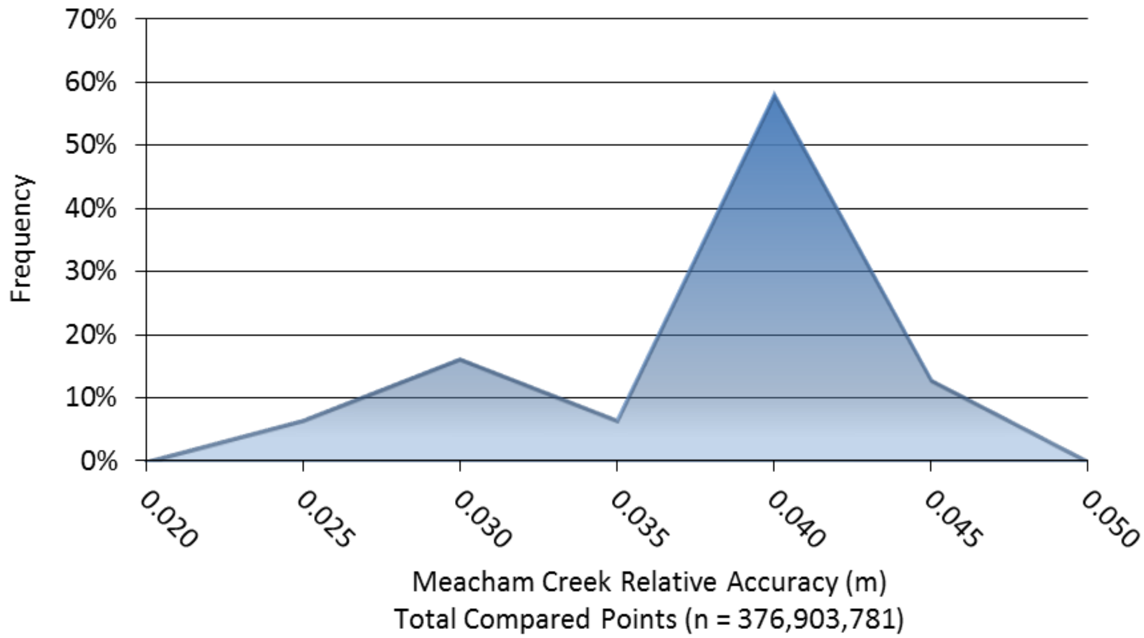
Dillon Dam AOI



Birch Creek Streams AOI



Meacham Creek AOI



Dillon Dam AOI