LiDAR Remote Sensing Data Collection:
Ravalli County, Montana

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1. Overview

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the Ravalli County Phase II and Trapper areas of interest (AOIs) in the Bitterroot Valley, Montana on October 23rd – 27th and November 1st-14th, 2009. The total area of delivered LiDAR for Ravalli County is 138,240 acres (**Figure 1**). The requested area was expanded to include a 100 m buffer to ensure complete coverage and adequate point densities around survey area boundaries. Due to snow accumulation, 1,327 requested acres were not collected in 2009 and will be delivered at a later date. See Figure 1 for area not included in this delivery.

Figure 1. Ravalli County survey area.
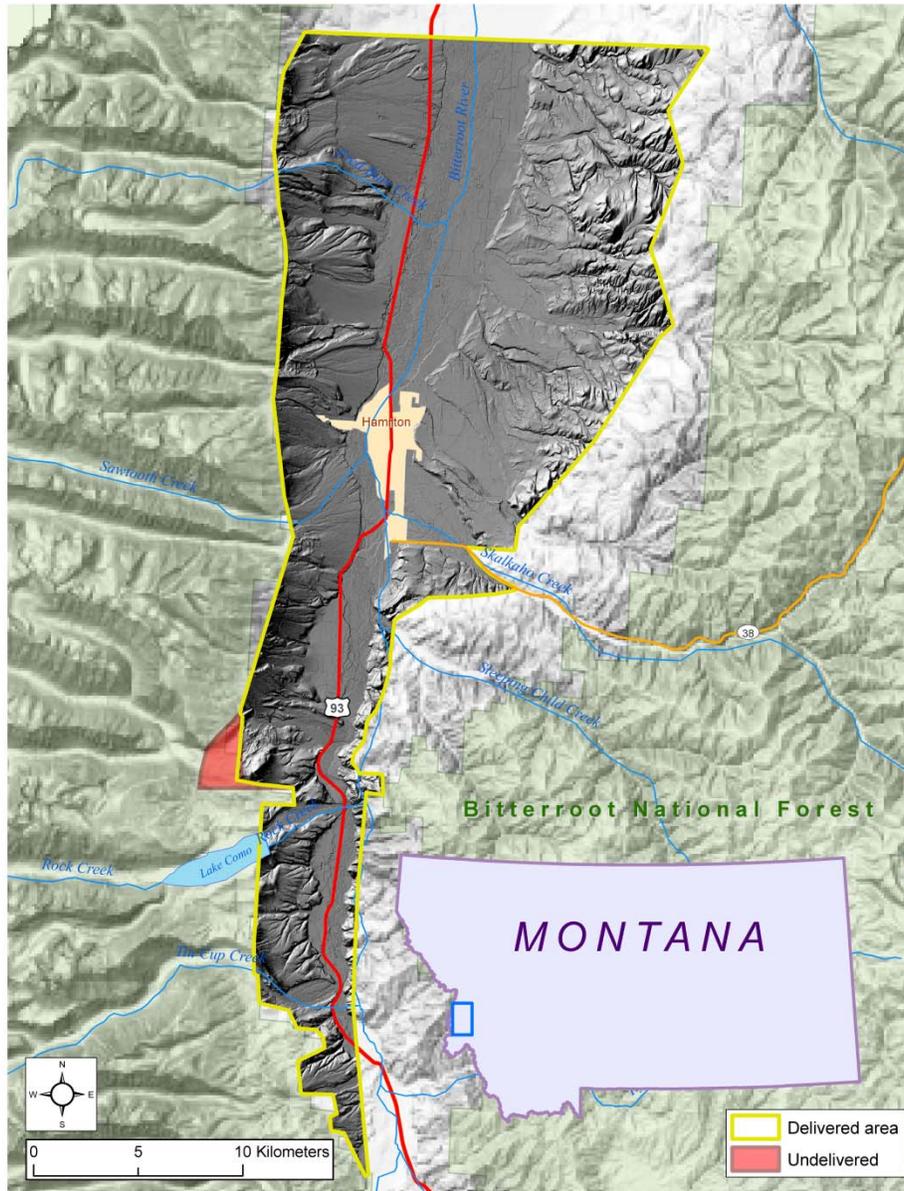
2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

Our LiDAR survey uses a Leica ALS50 Phase II laser system. For the Ravalli County survey area, the sensor scan angle was ±15° from nadir[1] with a pulse rate designed to yield an average native density (number of pulses emitted by the laser system) of ≥ 6 points per square meter over terrestrial surfaces. 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.

All survey areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) to reduce laser shadowing and increase surface laser painting. The Leica ALS50 Phase II system allows up to four range measurements (returns) per pulse, and all discernable laser returns were processed for the output dataset. This survey was planned at an altitude of 900m yielding an approximate swath width of 448m.

At a 900m altitude, the diameter of the ALS50

laser pulse on the ground is 21cm.

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".

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2.2 Ground Survey – Instrumentation and Methods

The following ground survey data 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. The horizontal and vertical coordinates of base station controls used for the Ravalli LiDAR survey were certified by River Design Group, Inc (Andy Belski, PLS # 14731). The certification report is attached.

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**). 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. Control monuments were located within 13 nautical miles of the survey area(s).
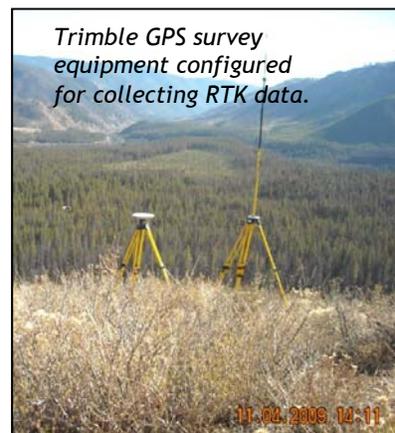

Trimble GPS survey equipment configured for collecting RTK data.

Table 1. Base Station Survey Control coordinates for the Ravalli County survey area.

Base Station ID	Datum: NAD83 (CORS91)		GRS80
	Latitude	Longitude	Ellipsoid Z (feet)
DGLI_22	N46°19'06.85459"	W113°57'20.22153"	6119.967
DGLI_EG1	N46°17'53.35618"	W114°01'47.53490"	3884.550
METCALF	N46°33'16.00207"	W114°04'35.85533"	3212.411
STEVI	N46°31'45.70268"	W114°03'05.89072"	3511.823
WSI_1	N46°17'15.03984"	W114°05'41.76265"	3619.571
WSI_2	N46°17'15.51836"	W114°03'58.63586"	3743.833
WSI-3	N46°17'53.37372"	W114°01'47.44318"	3884.574
WSI-4	N46°17'40.32164"	W114°10'57.31915"	3573.388
WSI_7	N46°02'33.27010"	W114°11'40.54557"	3990.376
WSI_8	N45°58'44.80286"	W114°09'20.23354"	3909.719

2.2.2 RTK Survey

To assess LiDAR data accuracy, ground truth points were collected using GPS based real-time kinematic (RTK) surveying. This allows for precise location measurements with an error (σ) of ≤ 1.5 cm (0.6 in). 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 survey control monuments. Instrumentation includes multiple Trimble DGPS units (R8). For the Ravalli County survey area, in addition to WS-collected RTK, River Design Group provided RTK points to compare absolute accuracy between land cover types. **Figure 2** portrays the distribution of RTK point locations used for the Ravalli County survey area.

Figure 2.   RTK and control monument locations used for the Ravalli County survey area.
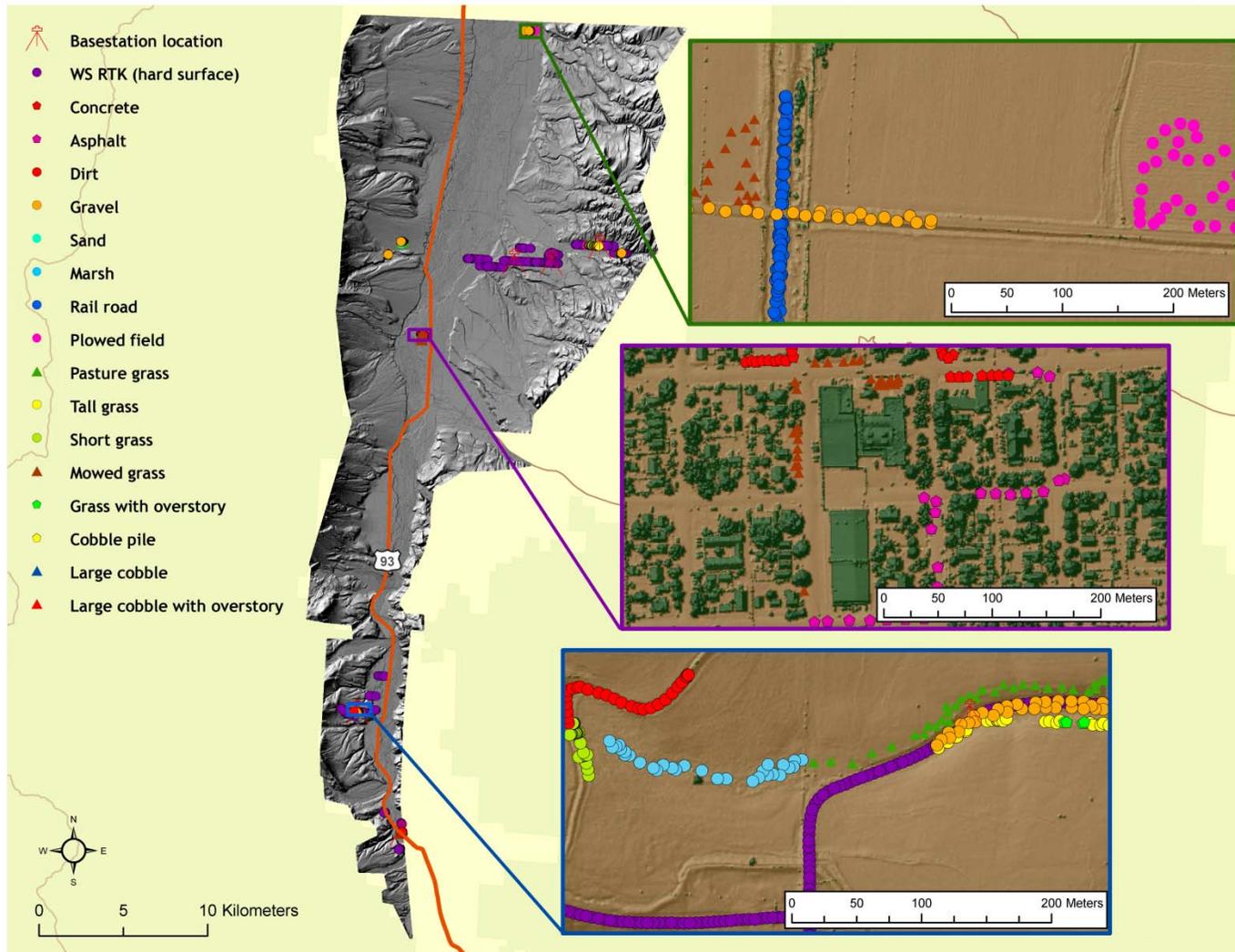
3. LiDAR Data Processing

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 v. 1.2) format.
   Software: ALS Post Processing Software v.2.69

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.9.017

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.9.004

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 1 –meter pixel resolution.
   Software: TerraScan v.9.017, ArcMap v. 9.3.1, TerraModeler v.9.003

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. 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.1.4 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 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. 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.

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 compare 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 ~ 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 calibrate laser accuracy for the LiDAR dataset, WS collected 3249 RTK points on hard surfaces within the study area. An additional 1119 RTK points were also collected by RDG, Inc. in various land covers to assess LiDAR accuracy among those land cover types. **Table 3** shows absolute accuracy statistics for all land cover types measured.

5. Study Area Results

Summary statistics for point resolution and accuracy (relative and absolute) of the LiDAR data collected in the Ravalli County 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 bin).

5.1 Data Summary

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

	Targeted	Achieved
Resolution:	≥ 6 points/m^2	5.93 points/m^2
*Vertical Accuracy (1 σ):	<30 cm	2.7 cm

* Based on 3249 hard-surface control points

5.2 Data Density/Resolution

The average first-return density of the delivered dataset is slightly below target density at 5.93 points per square meter (**Table 2**). 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).

Ground classifications were derived from automated ground surface modeling and manual, supervised classifications where it was determined that the automated model had failed. Ground return densities will be lower in areas of dense vegetation, water, or buildings.
The maps in **Figure 5** & **6** show the distribution of native and ground densities averaged per processing bin.

LiDAR data resolution for the Ravalli County survey area:

- Average Point (First Return) Density = 5.93 points/m^2
- Average Ground Point Density = 3.88 points/m^2

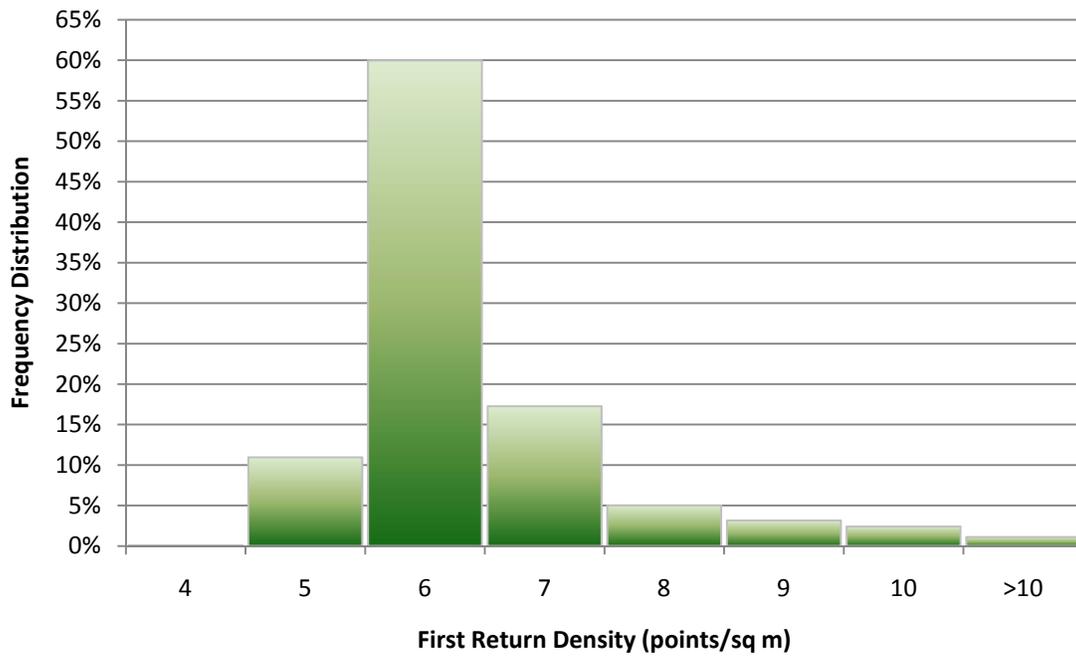*Figure 3. Density distribution for first return laser points.*

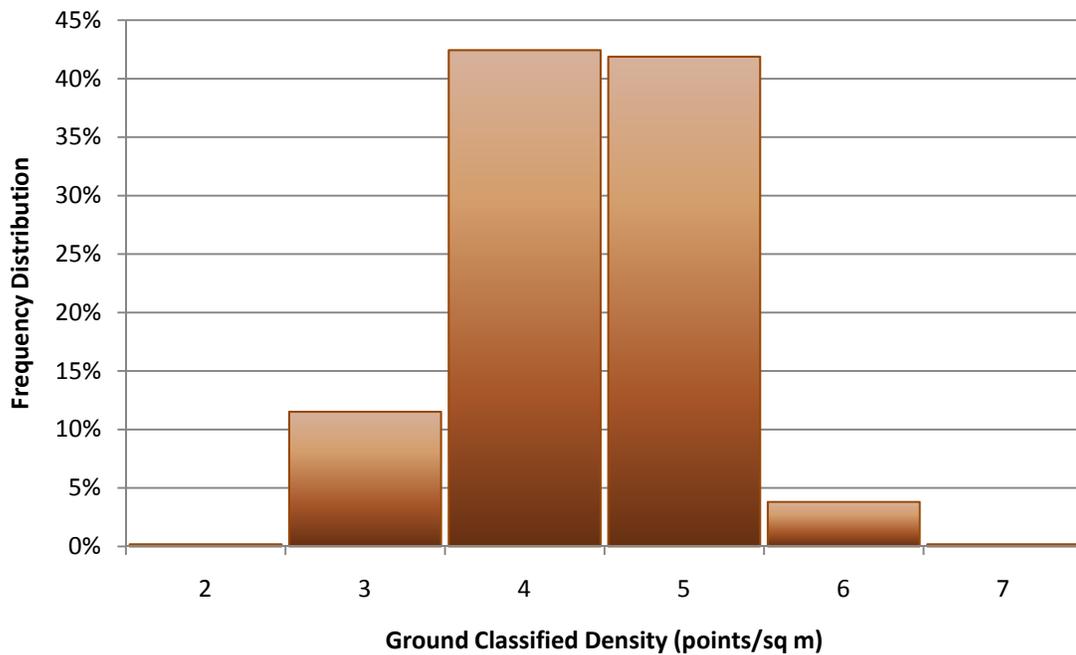*Figure 4. Density distribution for ground-classified laser points.*

Figure 5. Ravalli County density distribution map for first return points.
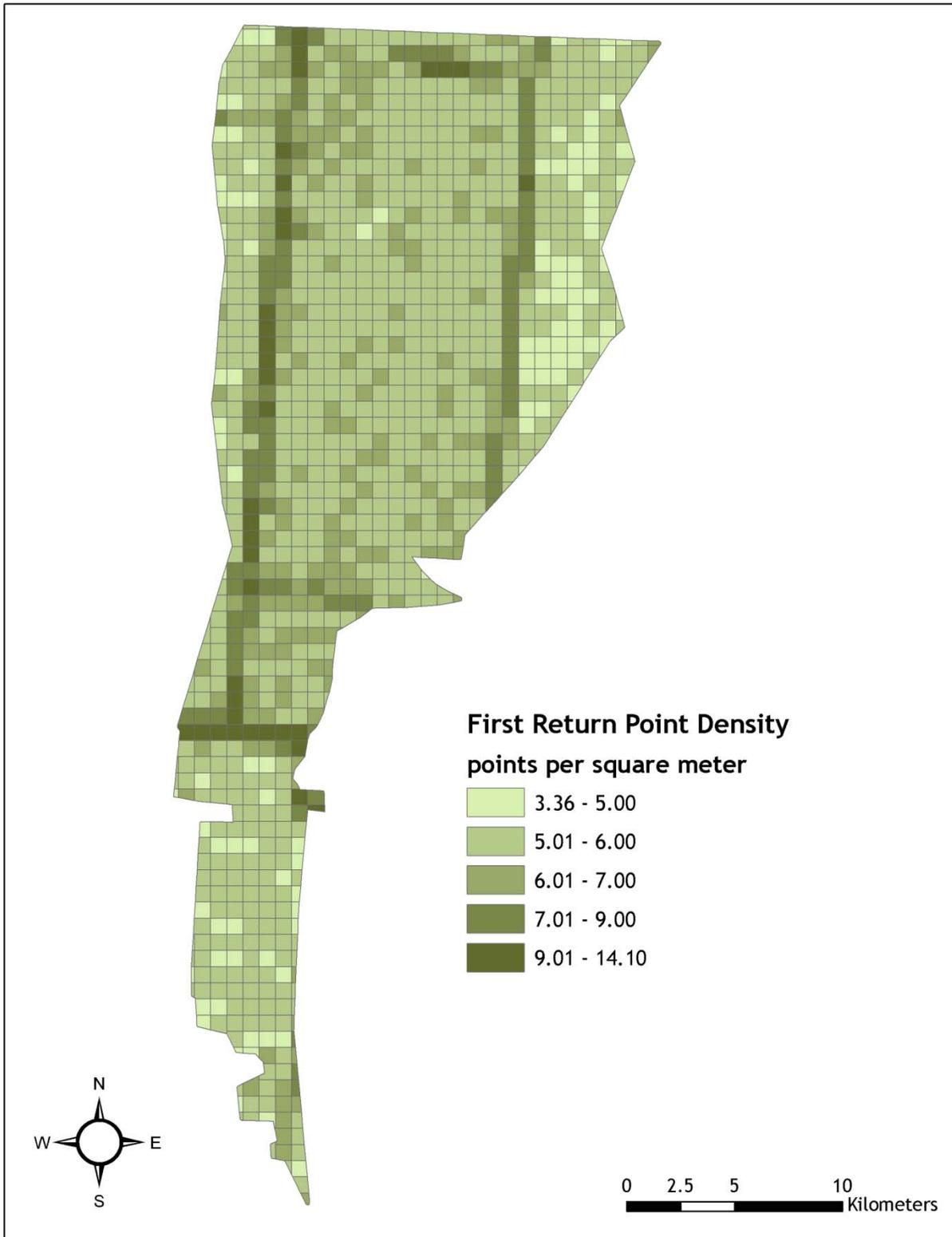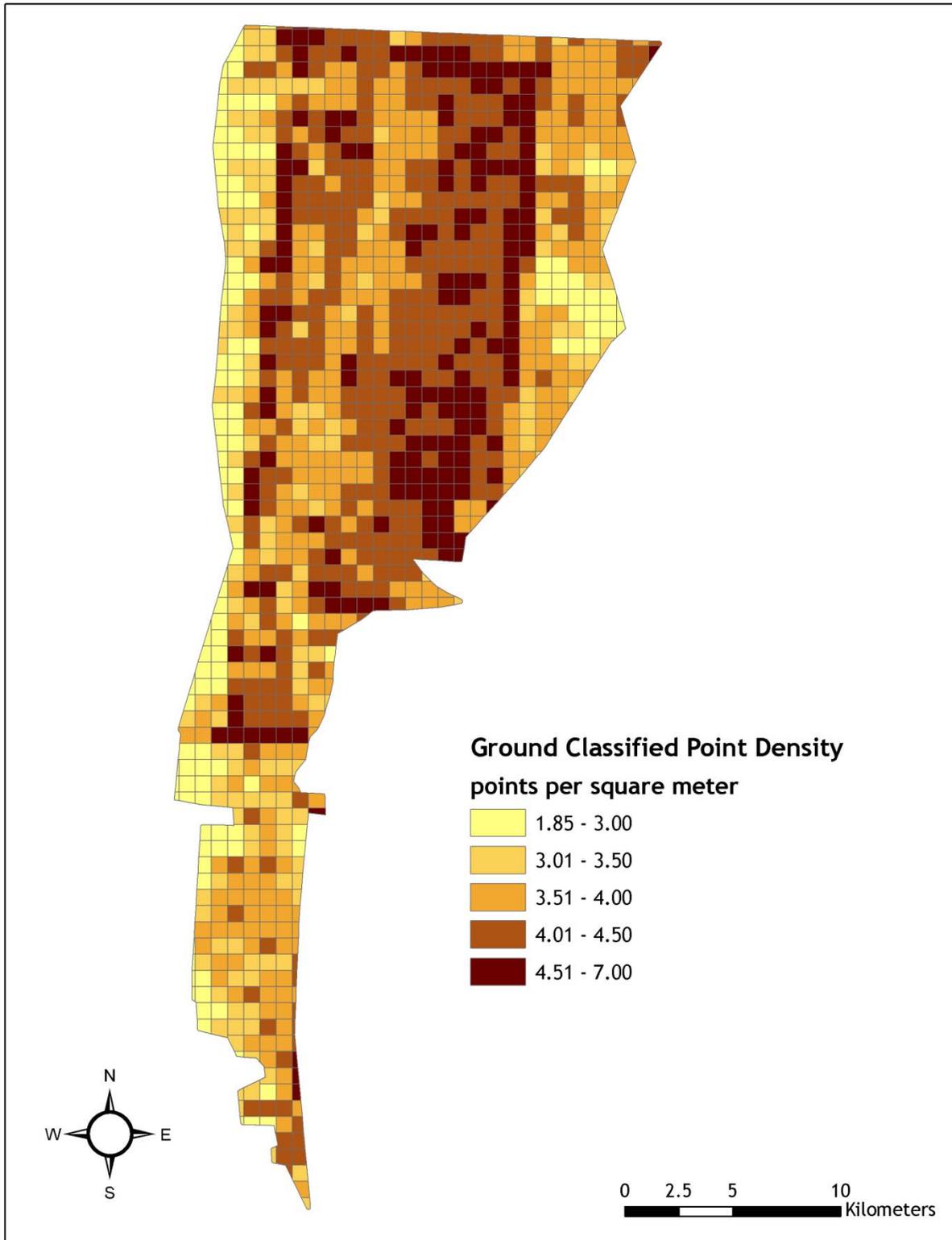

First Return Point Density
points per square meter

	3.36 - 5.00
	5.01 - 6.00
	6.01 - 7.00
	7.01 - 9.00
	9.01 - 14.10

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Figure 6. Ravalli County density distribution map for ground classified points.

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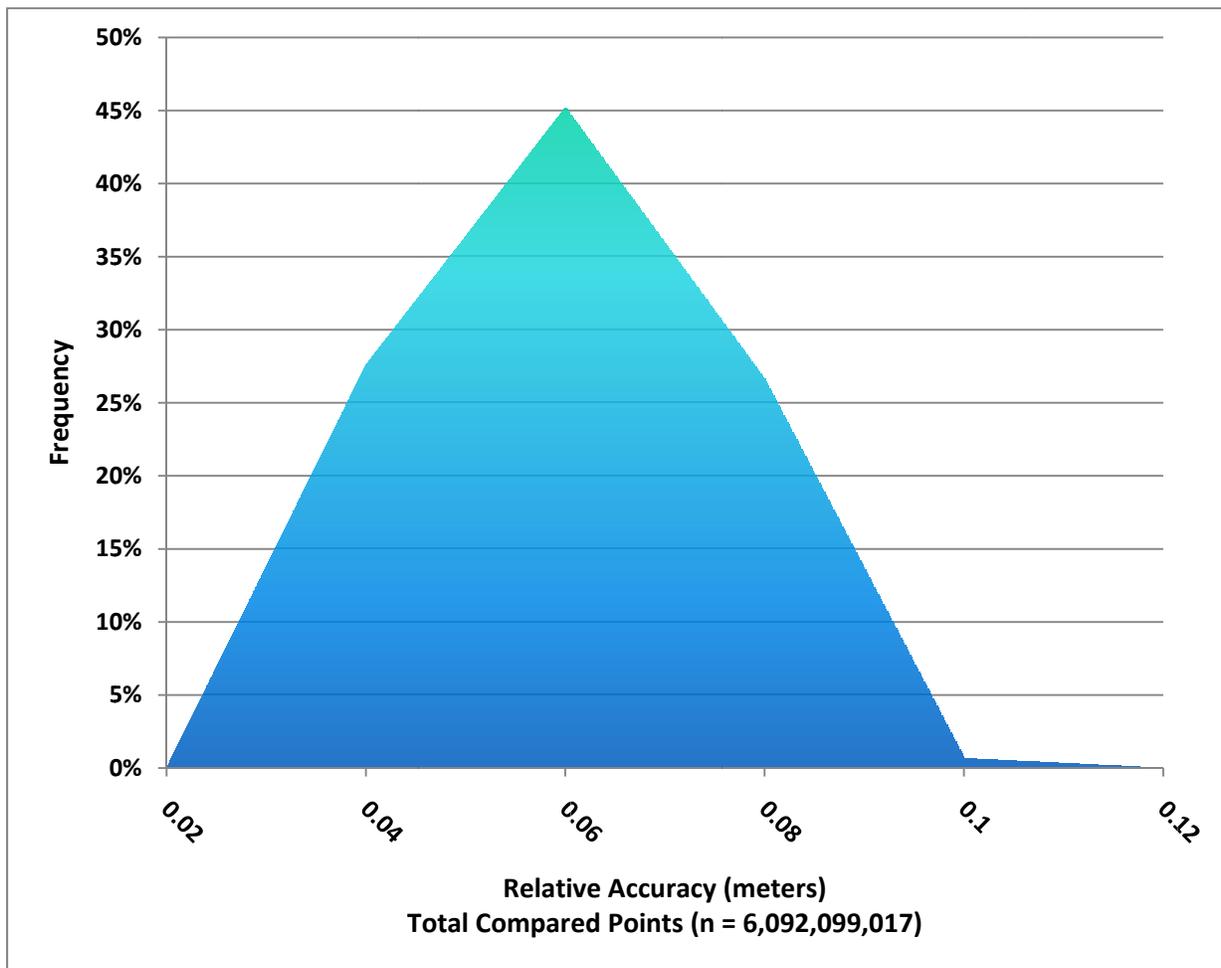
Prepared by Watershed Sciences, Inc.

5.3 Relative Accuracy Calibration Results

Relative accuracies for the Ravalli County survey area:

- o Project Average = 0.044m
- o Median Relative Accuracy = 0.050m
- o 1σ Relative Accuracy = 0.057m
- o 2σ Relative Accuracy = 0.073m

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

5.4 Absolute Accuracy

Absolute accuracies for the Ravalli County survey area:

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

RTK Surface Type	RTK Survey Sample Size (n)	Root Mean Square Error (RMSE)	Standard Deviations		Minimum Δz	Maximum Δz	Average Δz
			1 sigma (σ)	*2 sigma (σ)*			
Hard-surface (WS)	3249	0.09 ft (0.028 m)	0.087 ft (0.027 m)	0.18 ft (0.05 m)	-0.39 ft (-0.12 m)	0.28 ft (0.09 m)	-0.004 ft (-0.001 m)
Asphalt	159	0.17 ft (0.050 m)	0.19 ft (0.06 m)	0.28 ft (0.08 m)	-0.26 ft (-0.08 m)	0.32 ft (0.10 m)	0.12 ft (0.04 m)
Concrete	70	0.20 ft (0.062 m)	0.23 ft (0.07 m)	0.29 ft (0.09 m)	0.02 ft (0.01 m)	0.34 ft (0.10 m)	0.19 ft (0.06 m)
Dirt	45	0.30 ft (0.090 m)	0.32 ft (0.10 m)	0.41 ft (0.12 m)	-0.51 ft (-0.15 m)	0.47 ft (0.14 m)	0.24 ft (0.07 m)
Gravel	174	0.17 ft (0.050 m)	0.20 ft (0.06 m)	0.27 ft (0.08 m)	-0.20 ft (-0.06 m)	0.45 ft (0.14 m)	0.16 ft (0.05 m)
Cobble pile	62	0.15 ft (0.047 m)	0.16 ft 0.05 m	0.44 ft (0.13 m)	-0.88 ft (-0.27 m)	0.44 ft (0.13 m)	-0.03 ft (-0.01 m)
Large cobble	28	0.74 ft (0.22 m)	0.83 ft (0.25 m)	1.30 ft (0.39 m)	-1.4 ft (-0.42 m)	0.83 ft (0.25 m)	-0.35 ft (-0.11 m)
Large cobble with overstory	20	0.39 ft (0.12 m)	0.028 ft 0.085 m	0.80 ft (0.24 m)	-0.44 ft (-0.13 m)	0.85 ft (0.26 m)	0.08 ft (0.02 m)
Plowed field	68	0.25 ft (0.08 m)	0.28 ft (0.09 m)	0.40 ft (0.12 m)	-0.28 ft (-0.09 m)	0.44 ft (0.13 m)	0.21 ft (0.06 m)
Grass with overstory	20	0.49 ft (0.15 m)	0.41 ft (0.12 m)	1.00 ft (0.32 m)	-0.15 ft (-0.05 m)	1.10 ft (0.32 m)	0.37 ft (0.11 m)

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

RTK Surface Type	RTK Survey Sample Size (n)	Root Mean Square Error (RMSE)	Standard Deviations		Minimum Δz	Maximum Δz	Average Δz
			1 sigma (σ)	2 sigma (σ)			
Pasture grass	65	0.26 ft (0.08 m)	0.28 ft (0.08 m)	0.36 ft (0.11 m)	0.13 ft (0.04 m)	0.42 ft (0.13 m)	0.25 ft (0.08 m)
Mowed grass	100	0.22 ft (0.07 m)	0.24 ft (0.07 m)	0.38 ft (0.12 m)	-0.016 ft (-0.004 m)	0.42 ft (0.13 m)	0.20 ft (0.06 m)
Short grass	58	0.43 ft (0.13 m)	0.36 ft 0.11 m	0.82 ft (0.25 m)	0.06 ft (0.02 m)	1.10 ft (0.35 m)	0.37 ft (0.11 m)
Tall grass	101	0.47 ft (0.14 m)	0.49 ft (0.15 m)	0.73 ft (0.22 m)	-0.42 ft (-0.13 m)	1.2 ft (0.38 m)	0.42 ft (0.13 m)
Rail road	89	0.27 ft (0.08 m)	0.31 ft (0.09 m)	0.53 ft (0.16 m)	-0.75 ft (-0.23 m)	0.23 ft (0.07 m)	-0.13 ft (-0.04 m)
Marsh	30	0.55 ft (0.17 m)	0.59 ft (0.18 m)	0.82 ft (0.25 m)	0.25 ft (0.07 m)	0.95 ft (0.29 m)	0.53 ft (0.16 m)
Sand	30	0.82 ft (0.25 m)	0.84 ft (0.25 m)	1.10 ft (0.34 m)	0.24 ft (0.07 m)	2.10 ft (0.65 m)	0.74 ft (0.23 m)

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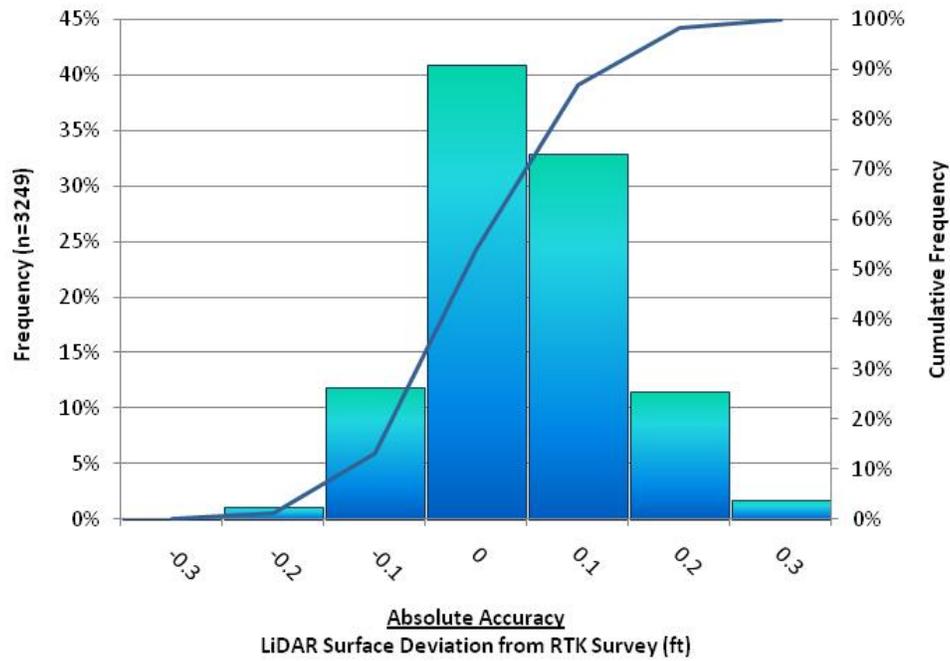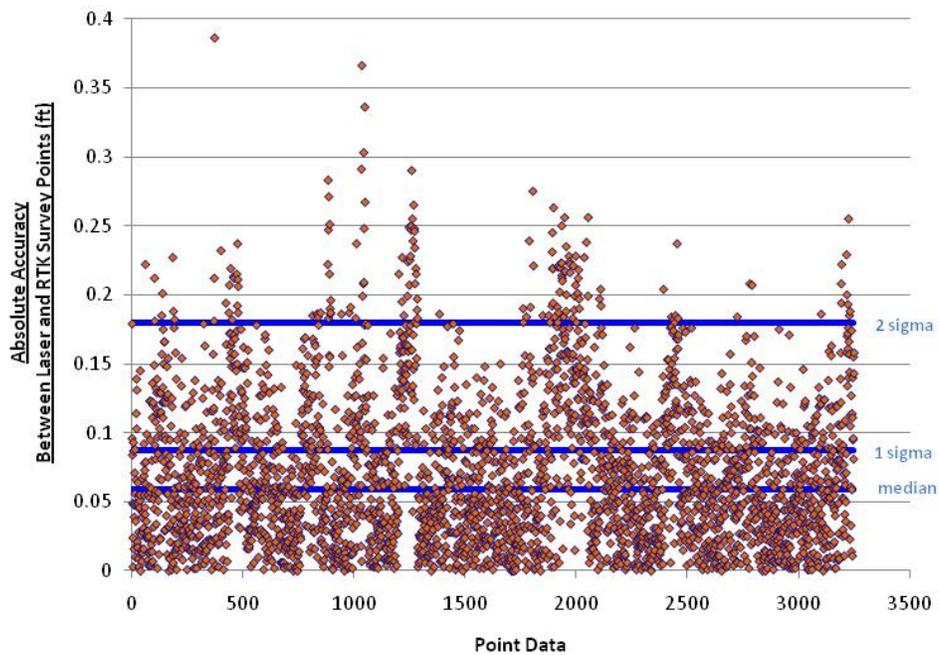*Figure 8. Absolute Accuracy - Histogram Statistics, based on RTK hard surface points.*

Figure 9. *Absolute Accuracy - Absolute deviation, based on RTK hard surface points.*

6. Projection/Datum and Units

Projection:		Montana State Plane
Datum	**Vertical:**	NAVD88 Geoid03
	Horizontal:	NAD83
Units	**Vertical:**	U.S. Survey Feet
	Horizontal:	Meters

7. Deliverables

Point Data:	• All Returns (LAS 1.2 format)
Vector Data:	• Tile Index of LiDAR points (shapefile format) • 2-ft Contours (AutoCad and shapefile format)
Raster Data:	• Elevation models (1 m resolution) • Bare Earth Model (ESRI GRID format) • Highest Hit Model (ESRI GRID format) • Intensity images (GeoTIFF format, 0.5 m resolution)
Data Report:	Full report containing introduction, methodology, and accuracy

8. Selected Images

Figure 10. 3D view looking North along Highway 93 at the confluence of Tin Cup Creek and Bitterroot River. The top image is derived from ground-classified LiDAR points and the bottom image is derived from the highest hit LiDAR points.
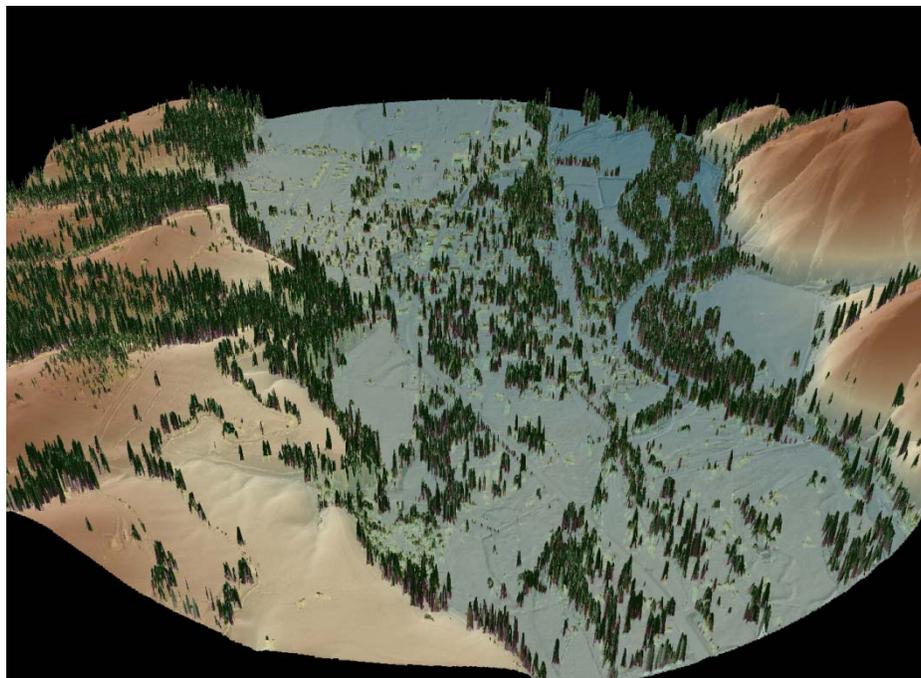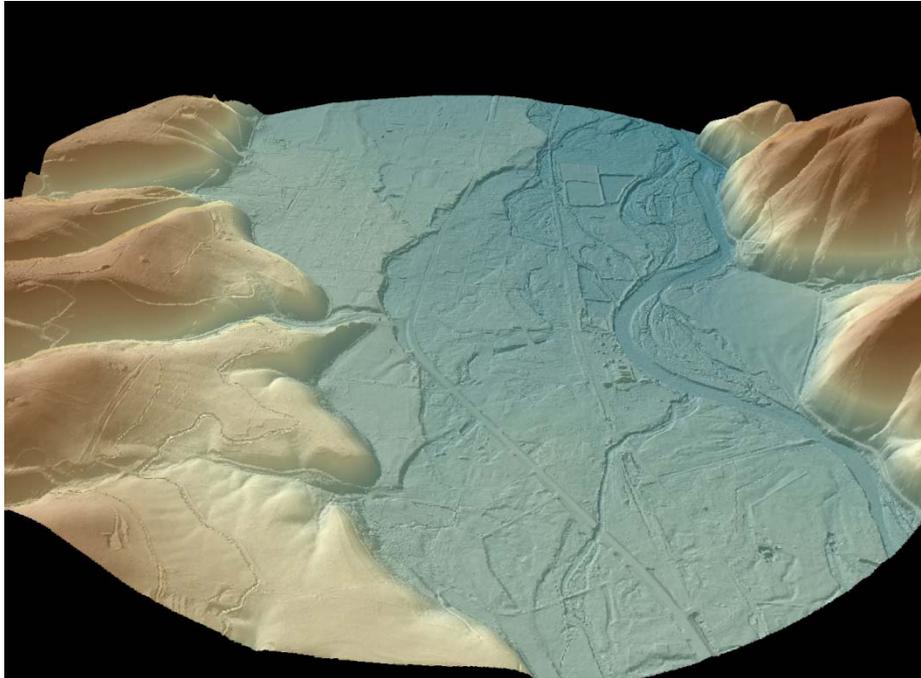
Figure 11. 3D view looking Northwest at the Bitterroot River with the city of Hamilton in the foreground. Highway 531 is crossing the river. The top image is derived from ground-classified LiDAR points and the bottom image is derived from the highest hit LiDAR points.
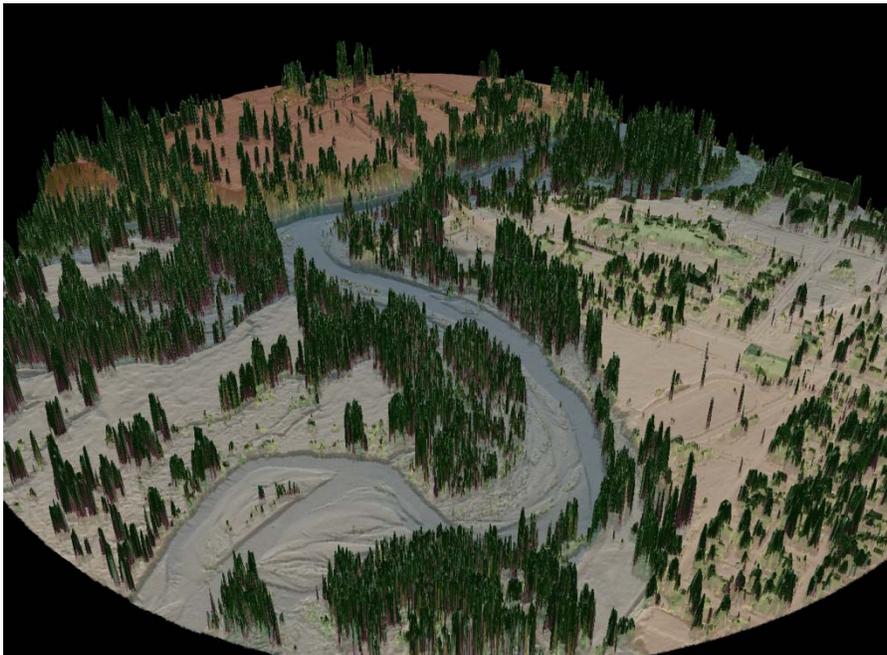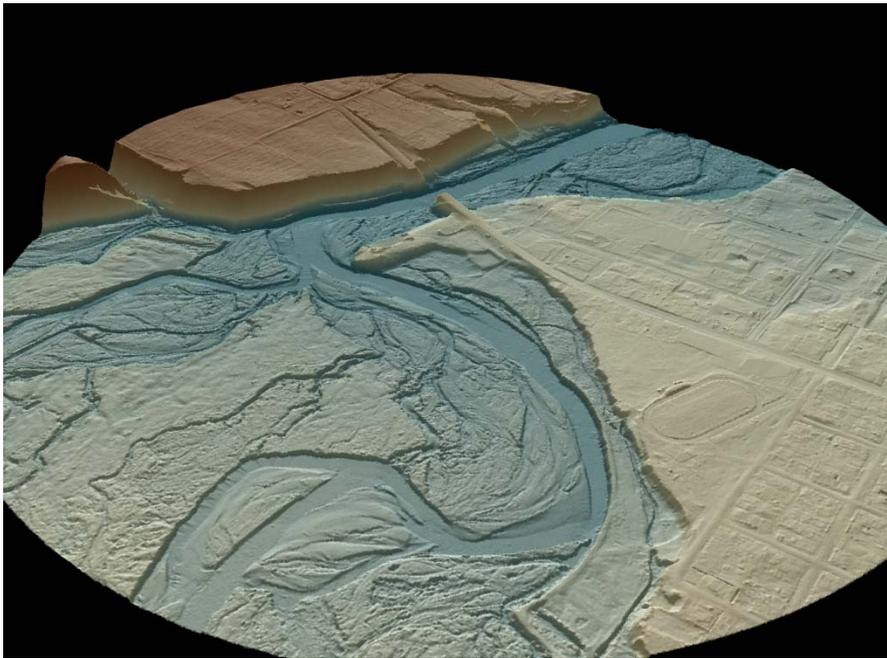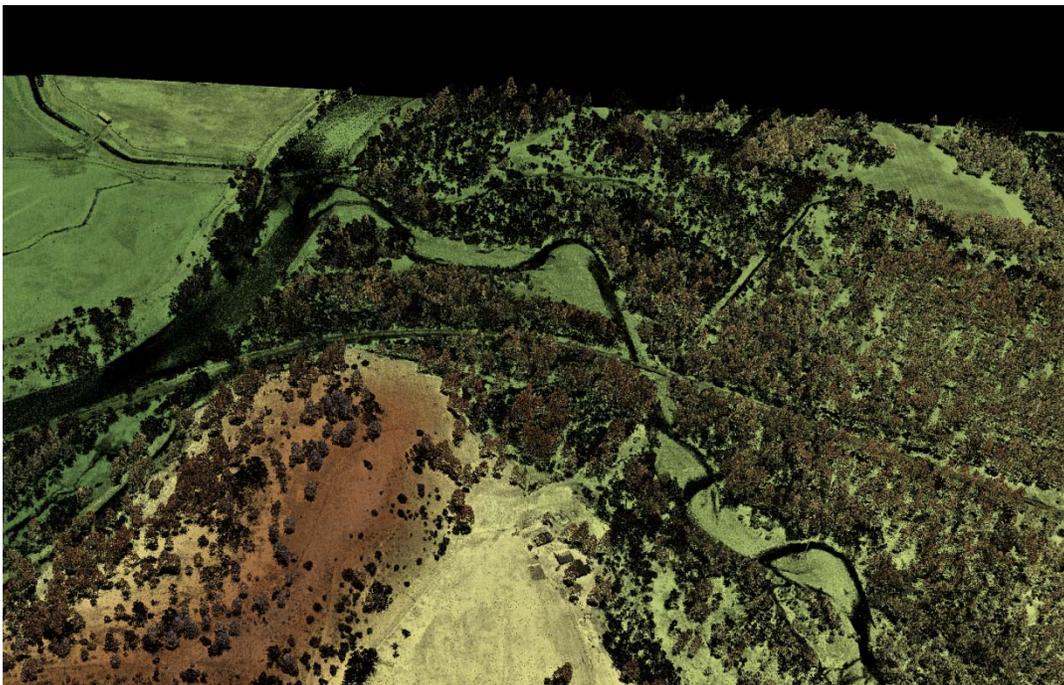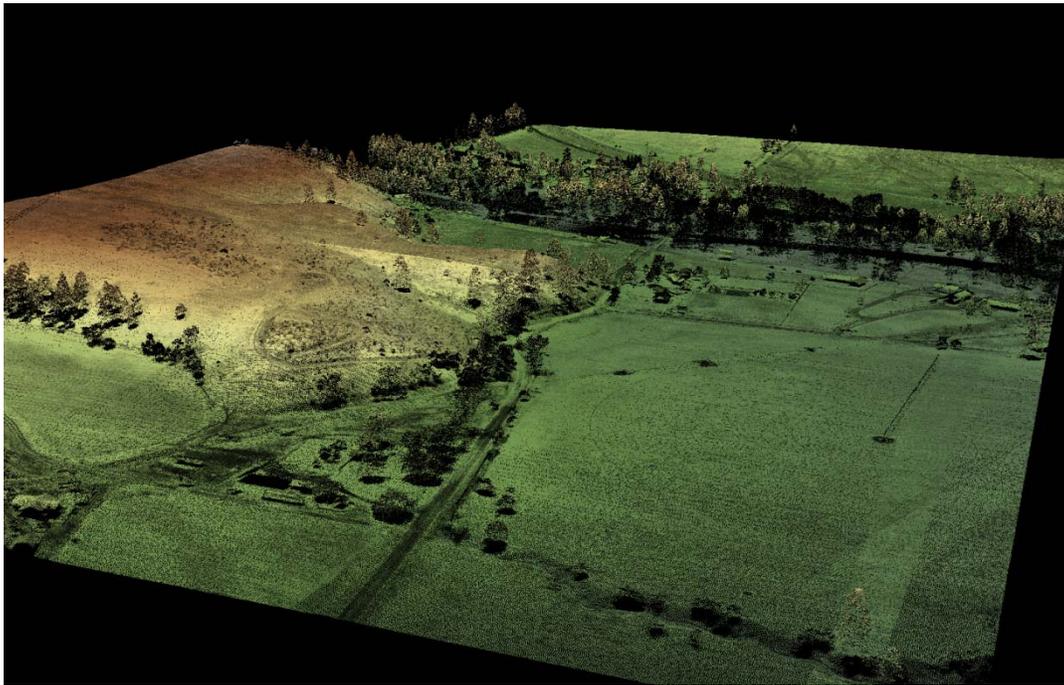
Figure 12. 3D views of LiDAR point clouds colored by elevation and shaded by intensity. Top image looking Southeast along Old Darby Road with the Bitterroot River in the background. Bottom image looking Northeast with Lost Horse Creek skirting the boundary.

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9. 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.

10. 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:
1. <u>Low Flight Altitude</u>: 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).
2. <u>Focus Laser Power at narrow beam footprint</u>: 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. <u>Reduced Scan Angle</u>: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of ±15° from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. <u>Quality GPS</u>: 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.
5. <u>Ground Survey</u>: 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.
6. <u>50% Side-Lap (100% Overlap)</u>: 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. <u>Opposing Flight Lines</u>: 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.