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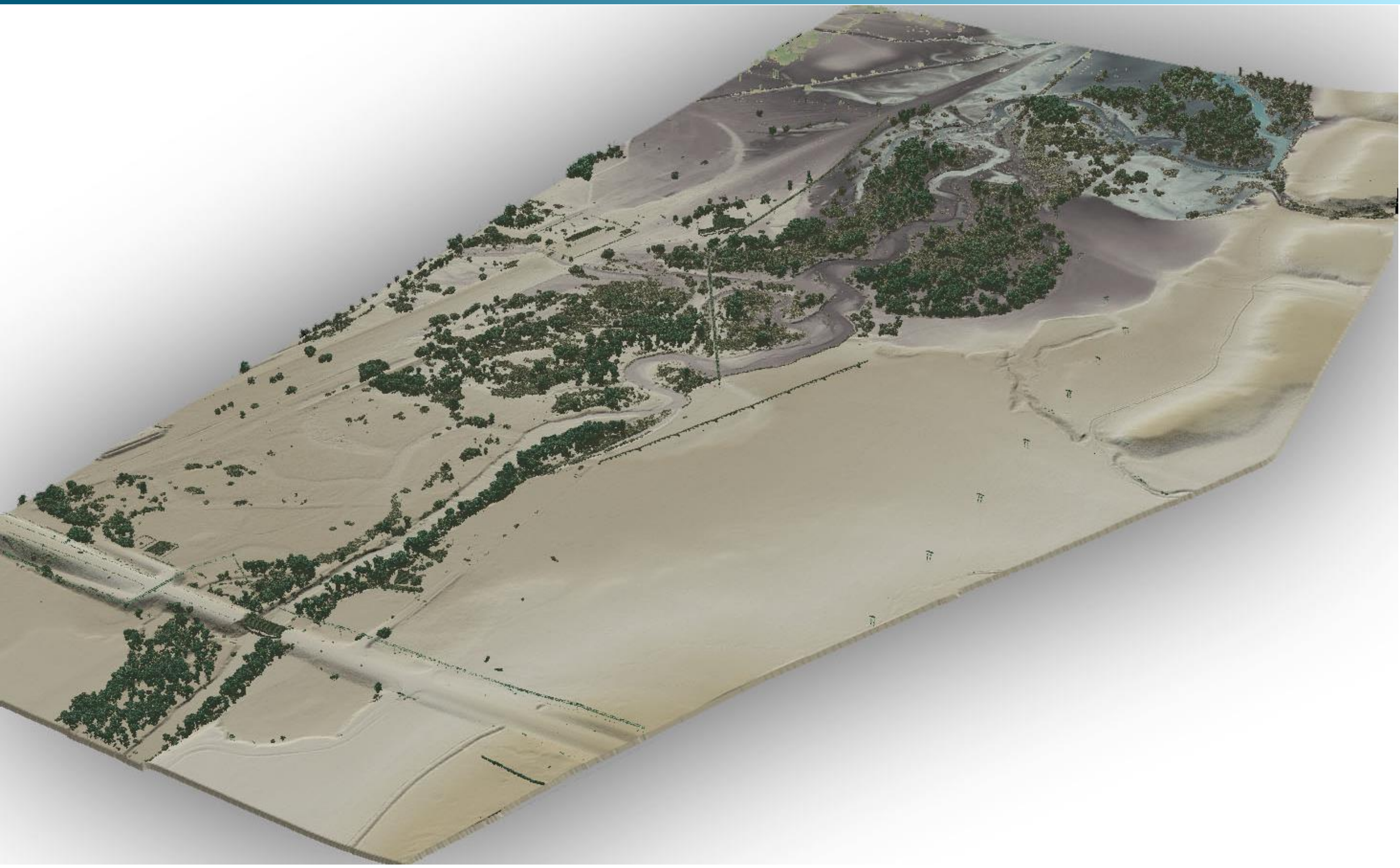

Harlowton AOI, Beaverhead County LiDAR Technical Data Report

The Montana Department of Natural Resources & Conservation

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Cover Photo: A view of the Harlowton AOI was created by the gridded bare earth model colored by elevation and overlaid with the above ground LiDAR returns colored by intensity.

INTRODUCTION

This photo taken by QSI acquisition staff shows a view of the Montana landscape and static GNSS equipment set up over monument CAL_08.

In September 2015, Quantum Spatial (QSI) was contracted by the Montana Department of Natural Resources and Conservation (DNRC) to collect Light Detection and Ranging (LiDAR) data in the winter of 2015 for the Beaverhead County LiDAR project in Montana. The Beaverhead County project encompasses two sites: the Harlowton, Montana area of interest (AOI) and the Dillon, Montana AOI. This primary delivery includes LiDAR data acquired for the Harlowton AOI only. Data were collected to aid the DNRC in assessing the topographic and geophysical properties of the study area to support floodplain mapping and hazard assessment.

This report accompanies the delivered LiDAR data and documents contract specifications, data acquisition procedures, processing methods, and analysis of the final dataset including LiDAR accuracy and density. Acquisition dates and acreage are shown in Table 1, a complete list of contracted deliverables provided to DNRC is shown in Table 2, and the project extent is shown in Figure 1.

Table 1: Acquisition dates, acreage, and data types collected on the Harlowton AOI site

Project Site	Contracted Acres	Buffered Acres	Acquisition Dates	Data Type
Harlowton AOI	4,961	5,966	11/14/2015	High resolution LiDAR

Deliverable Products

Table 2: Products delivered to DNRC for the Harlowton AOI

<table>
<tr><th colspan="2">Harlowton, Montana Products
Projection: UTM Zone 12 North
Horizontal Datum: NAD83 (2011)
Vertical Datum: NAVD88 (GEOID12A)
Units: Meters</th></tr>
<tr><td>Points</td><td>LAS v 1.4
All Returns
Raw Calibrated Flightline Swaths</td></tr>
<tr><td>Rasters</td><td>1.0 Meter Bare Earth Model
Bare Earth Model (ESRI Grid)
Bare Earth Model (ESRI Geodatabase)
Bare Earth Model (ASCII format)</td></tr>
<tr><td>Vectors</td><td>Shapefiles (*.shp)
Site Boundary
LiDAR Tile Index
Ground Survey Points
0.5 meter Contours Shapefiles
0.5 meter Contours in a File Geodatabase (*.gdb)</td></tr>
</table>

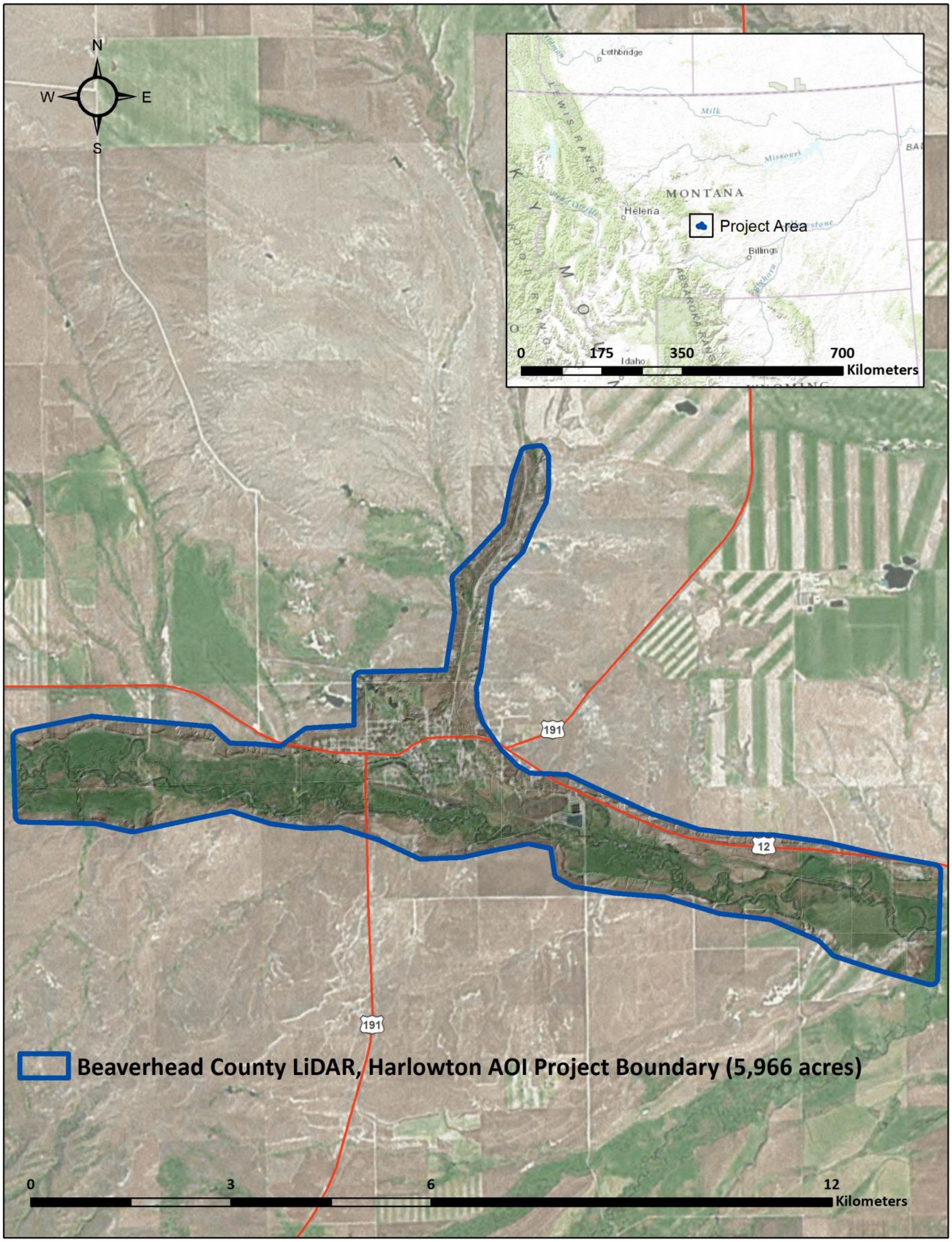


Figure 1: Location map of the Harlowton AOI site in Montana

QSI's Cessna Caravan

Planning

In preparation for data collection, QSI reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Harlowton AOI LiDAR study area at the target point density of ≥8.0 points/m^2. Acquisition parameters including orientation relative to terrain, flight altitude, pulse rate, scan angle, and ground speed were adapted to optimize flight paths and flight times while meeting all contract specifications.

Factors such as satellite constellation availability and weather windows must be considered during the planning stage. Any weather hazards or conditions affecting the flight were continuously monitored due to their potential impact on the daily success of airborne and ground operations. In addition, logistical considerations including private property access and potential air space restrictions were reviewed.

Airborne Survey

LiDAR

The LiDAR survey was accomplished using a Leica ALS80 system mounted in a Cessna Caravan 208B. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Harlowton AOI project area. The Leica ALS80 laser system can record unlimited range measurements (returns) per pulse. 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. The discrepancy between first return and overall delivered density will vary depending on terrain, land cover, and the prevalence of water bodies. All discernible laser returns were processed for the output dataset.

Table 3: LiDAR specifications and survey settings

LiDAR Survey Settings & Specifications	
Acquisition Dates	11/14/2015
Aircraft Used	Cessna Caravan 208B
Sensor	Leica ALS80
Survey Altitude (AGL)	1,800 m
Target Pulse Rate	310.8 kHz
Pulse Mode	Multiple Pulse in Air (2PiA)
Laser Pulse Diameter	45 cm
Mirror Scan Rate	58.4 Hz
Field of View	28^o
GPS Baselines	≤13 nm
GPS PDOP	≤3.0
GPS Satellite Constellation	≥6
Maximum Returns	Unlimited
Intensity	8-bit, scaled to 16-bit
Resolution/Density	Average 8 pulses/m^2
Accuracy	$RMSE_Z$ ≤ 15 cm

Leica ALS80 LiDAR sensor

All areas were surveyed with an opposing flight line side-lap of ≥50% (≥100% overlap) in order to reduce laser shadowing and increase surface laser painting. To accurately solve for laser point position (geographic coordinates x, y and 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, and 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 and sensor position and attitude data are indexed by GPS time.

Ground Control

Gaston Monument Cal_10.

Ground control surveys including monumentation, ground survey points (GSPs), and land cover class points were conducted by Gaston Engineering and Surveying, PC (Gaston). QSI occupied bases established by Gaston in order to geospatially correct the aircraft positional coordinate data, while Gaston provided ground check points and land cover class points to perform quality assurance checks on final LiDAR data.

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 the collection of QSI ground survey points using real time kinematic (RTK) survey techniques, to be used as an additional check only.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. QSI utilized two existing monuments provided by Gaston for the Harlowton AOI LiDAR project (Table 4, Figure 2).

Table 4: Monuments established for the Harlowton AOI acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00

Monument ID	Latitude	Longitude	Ellipsoid (meters)
CAL_08	46° 25' 25.16082"	-109° 46' 15.55679"	1250.285
CAL_10	46° 24' 22.39635"	-109° 44' 12.21686"	1249.301

Ground Survey Points (GSPs)

Ground survey points were collected by Gaston and provided to QSI to be used in accuracy assessment. All GSP 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. Relative errors for any GSP position must be less than 1.5 cm horizontal and 2.0 cm vertical in order to be accepted. GSPs were collected within as many flightlines as possible; however the distribution of GSPs depended on ground access constraints and monument locations and may not be equitably distributed throughout the study area (Figure 2).

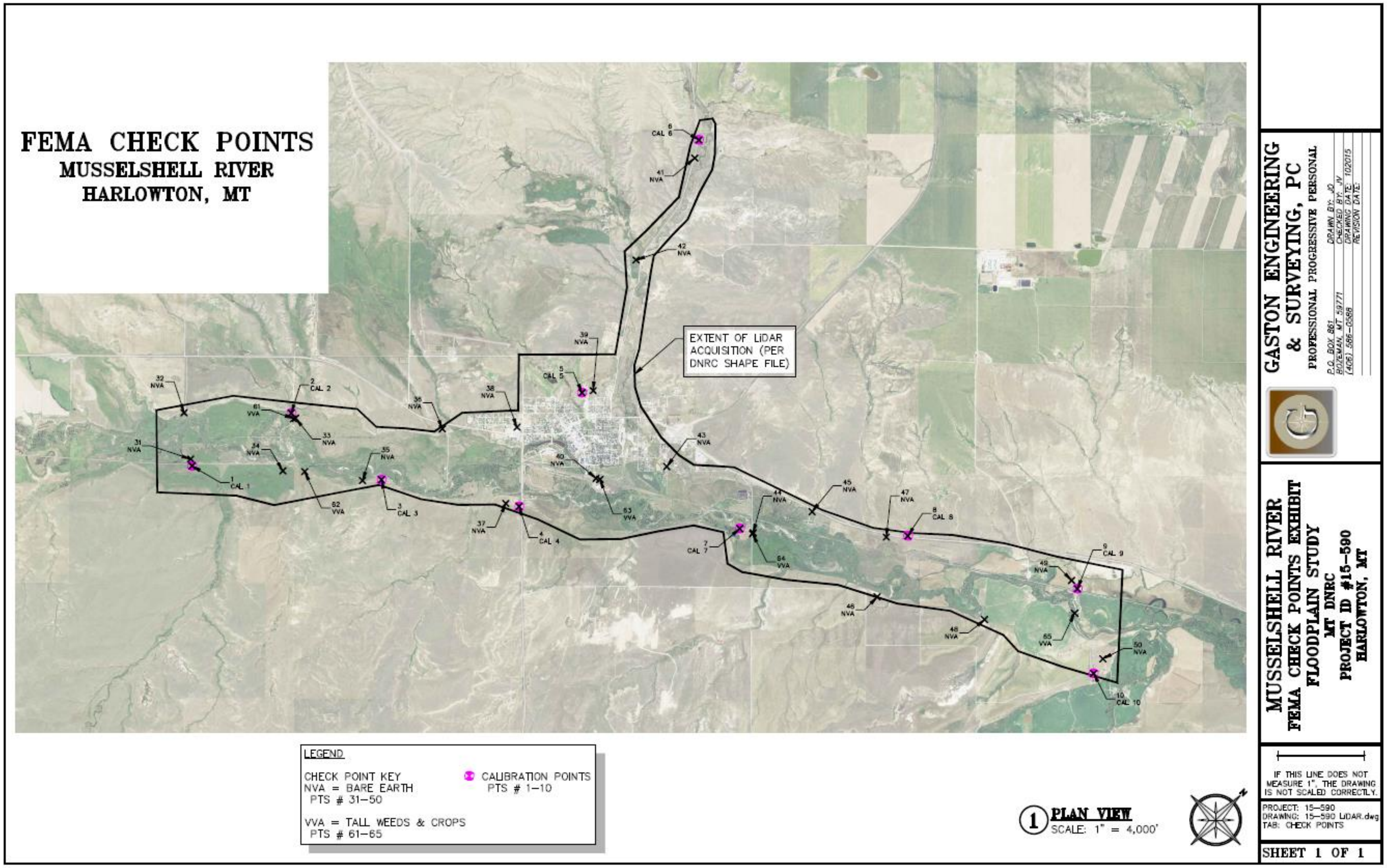


Figure 2: Gaston's ground survey location map

LiDAR Data

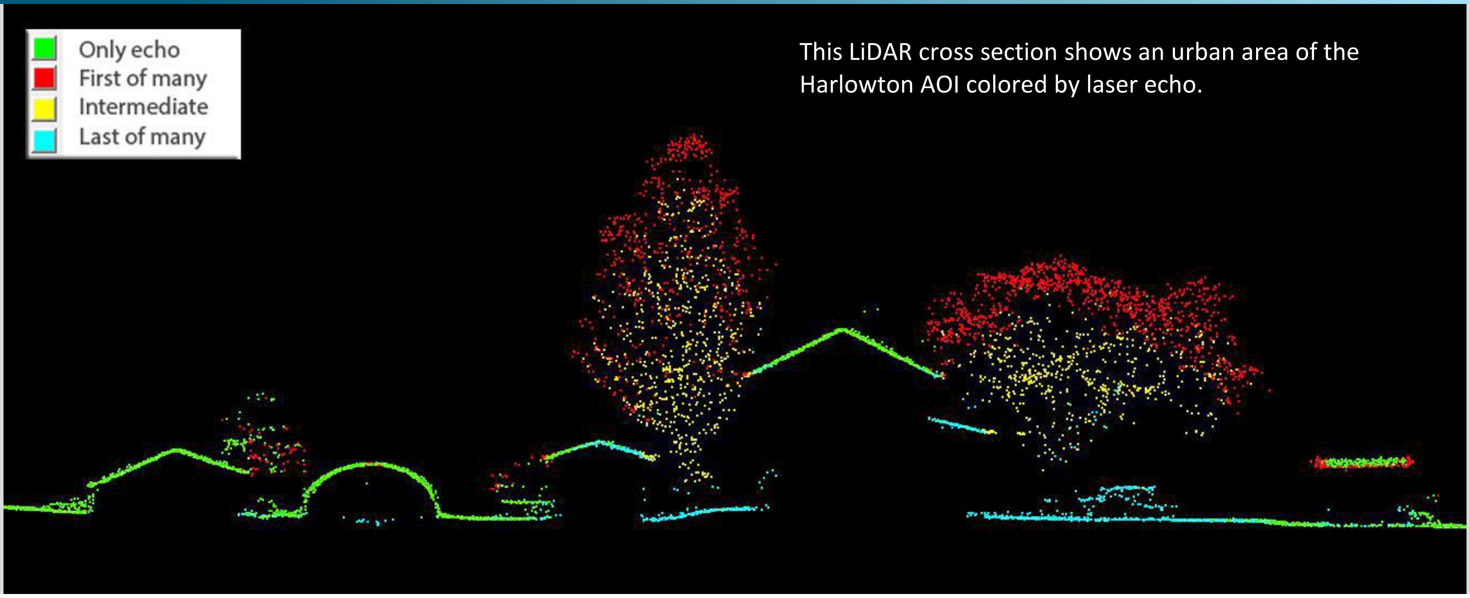
Upon completion of data acquisition, QSI processing staff initiated a suite of automated and manual techniques to process the data into the requested deliverables. Processing tasks included GPS control computations, smoothed best estimate trajectory (SBET) calculations, kinematic corrections, calculation of laser point position, sensor and data calibration for optimal relative and absolute accuracy, and LiDAR point classification (Table 5). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 6.

Table 5: ASPRS LAS classification standards applied to the Harlowton AOI dataset

Classification Number	Classification Name	Classification Description
1	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and man-made structures
2	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
7	Noise	Laser returns that are often associated with birds, scattering from reflective surfaces, or artificial points below the ground surface, including flagged withheld bit.
11	Withheld	Laser returns that have intensity values of 0 or 255, and flagged withheld bit.

Table 6: LiDAR processing workflow

LiDAR Processing Step	Software Used
Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data. Develop a smoothed best estimate of trajectory (SBET) file that blends post-processed aircraft position with sensor head position and attitude recorded throughout the survey.	Waypoint Inertial Explorer v.8.6
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. Convert data to orthometric elevations by applying a geoid12a correction.	Waypoint Inertial Explorer v.8.6 Leica Cloudpro v. 1.2.1
Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter erroneous points. Classify ground points for individual flight lines.	TerraScan v.15
Using ground classified points per each flight line, test the relative accuracy. Perform automated line-to-line calibrations for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calculate calibrations on ground classified points from paired flight lines and apply results to all points in a flight line. Use every flight line for relative accuracy calibration.	TerraMatch v.15
Classify resulting data to ground and other client designated ASPRS classifications (Table 5). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.15 TerraModeler v.15
Generate bare earth models as triangulated surfaces and export as ESRI GRIDs, ESRI Geodatabase, and ASCII format at a 1 meter pixel resolution.	TerraScan v.15 TerraModeler v.15 ArcMap v. 10.1



LiDAR Density

The acquisition parameters were designed to acquire an average first return density of 8 points/m^2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified LiDAR returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first return density of LiDAR data for the Harlowton AOI was 10.07 points/m^2 while the average ground classified density was 6.95 points/m^2 (Table 7). The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figure 3 through Figure 5.

Table 7: Average LiDAR point densities

Classification	Point Density
First Return	10.07 points/m^2
Ground Classified	6.95 points/m^2

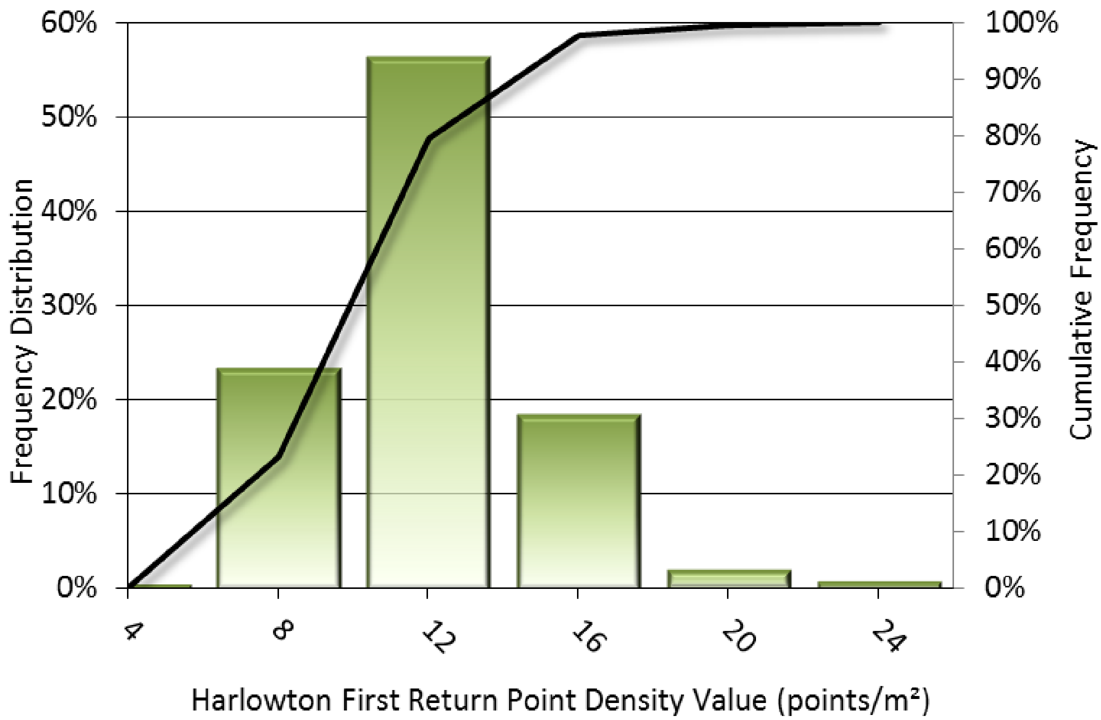


Figure 3: Frequency distribution of first return point density values per 100 x 100 m cell

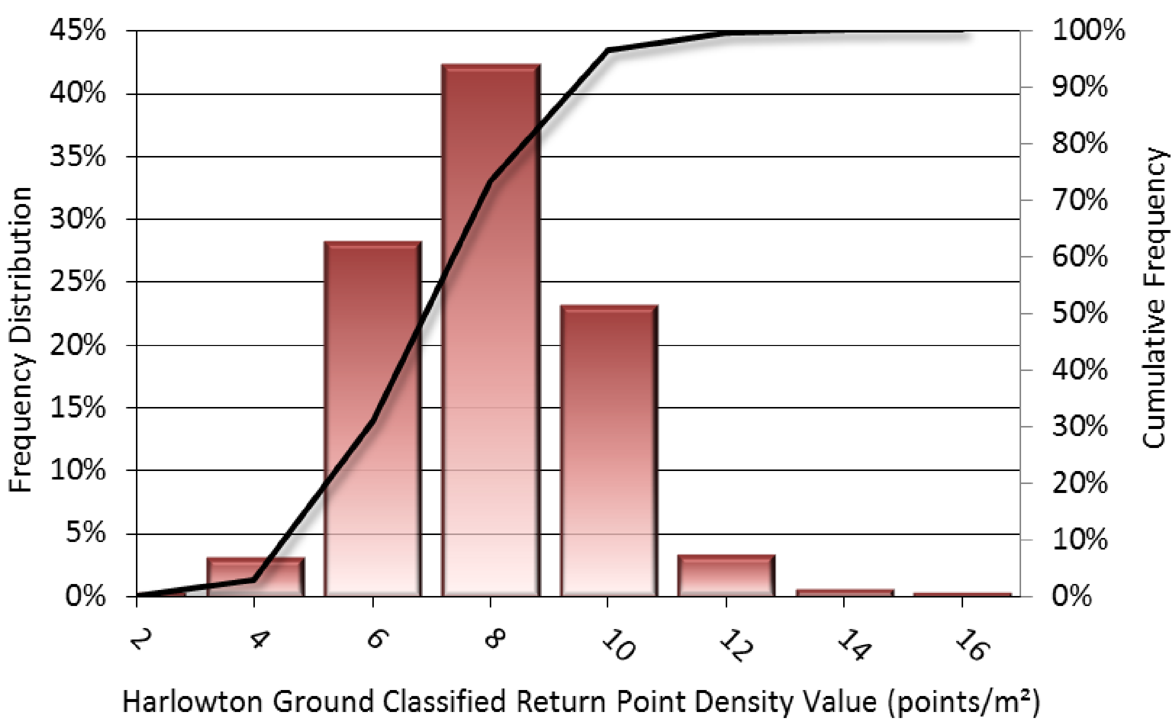


Figure 4: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

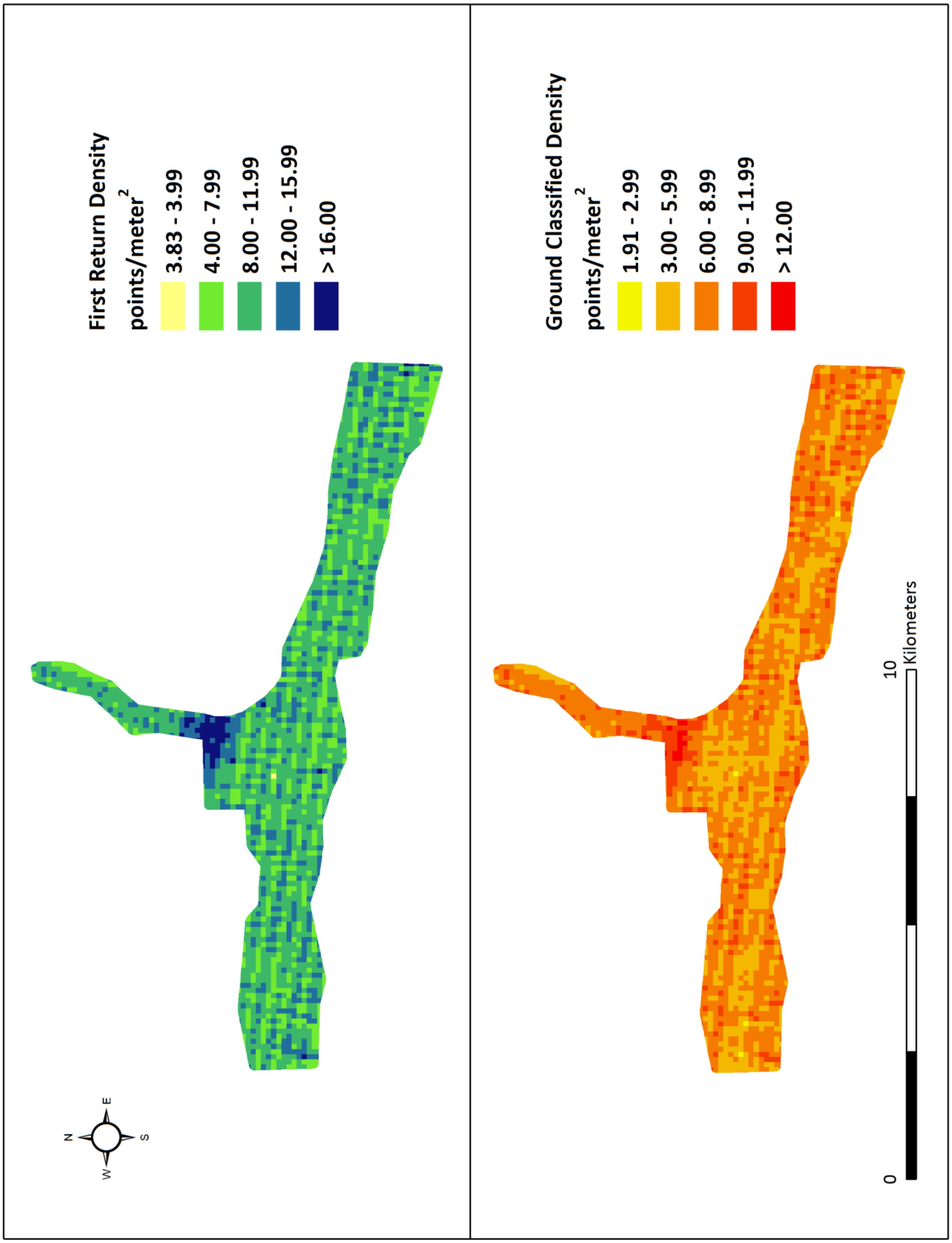


Figure 5: First return and ground-classified point density map for the Harlowton AOI site (100 m x 100 m cells)

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 Non-vegetated Vertical Accuracy

Non-vegetated Vertical Accuracy (NVA) was assessed according to guidelines presented in the ASPRS Positional Accuracy Standards for Digital Geospatial Data[1]. NVA compares known ground check point data collected on open, bare earth surfaces with level slope (<20°) to the triangulated 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 high probability of measuring the ground surface and is evaluated at the 95% confidence interval (1.96 * RMSE), as shown in Table 8.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from ground check point coordinates are also considered during accuracy assessment. 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 Harlowton AOI, 20 ground check points were withheld in total resulting in a fundamental vertical accuracy of 0.043 meters (Figure 6).

Table 8: NVA results

Non-vegetated Vertical Accuracy	
Sample	20 points
NVA (1.96*RMSE)	0.043 m
Average	-0.015 m
Median	-0.015 m
RMSE	0.022 m
Standard Deviation (1σ)	0.016 m

[1] ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014

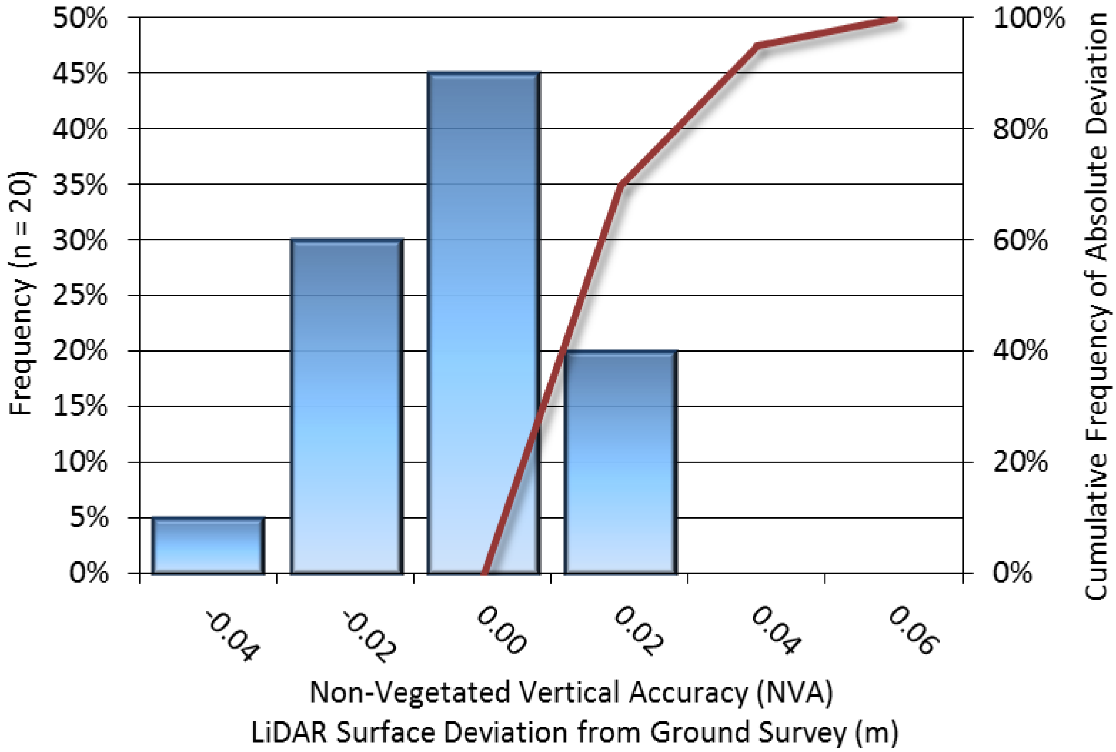


Figure 6: Frequency histogram for LiDAR surface deviation from ground check point values

LiDAR Vegetated Vertical Accuracy

QSI also assessed vertical accuracy using Vegetated Vertical Accuracy (VVA) reporting. VVA compares known ground check point data within all land cover class categories to the triangulated ground surface generated by the ground classified LiDAR points. VVA is evaluated at the 95th percentile, as shown in Table 9.

Table 9: Vegetated Vertical Accuracy of the Harlowton AOI

Vegetated Vertical Accuracy	
Sample	5 points
Average Dz	0.071 m
Median	0.081 m
RMSE	0.081 m
Standard Deviation (1σ)	0.044 m
95th Percentile	0.159 m

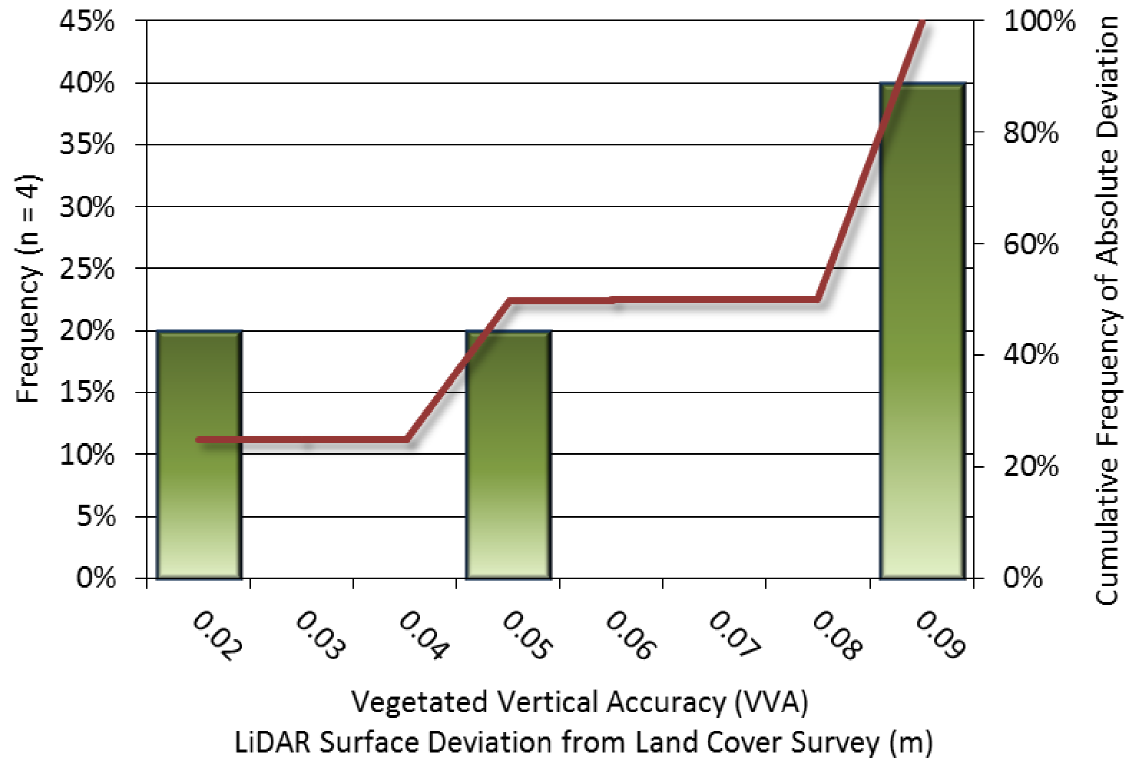


Figure 7: Frequency histogram for LiDAR surface deviation from all land cover class point values (VVA)

LiDAR Relative Vertical 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 was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the Harlowton AOI LiDAR was 0.025 meters (Table 10, Figure 8).

Table 10: Relative accuracy results

Relative Accuracy	
Sample	16 surfaces
Average	0.025 m
Median	0.025 m
RMSE	0.025 m
Standard Deviation (1σ)	0.001 m
1.96σ	0.002 m

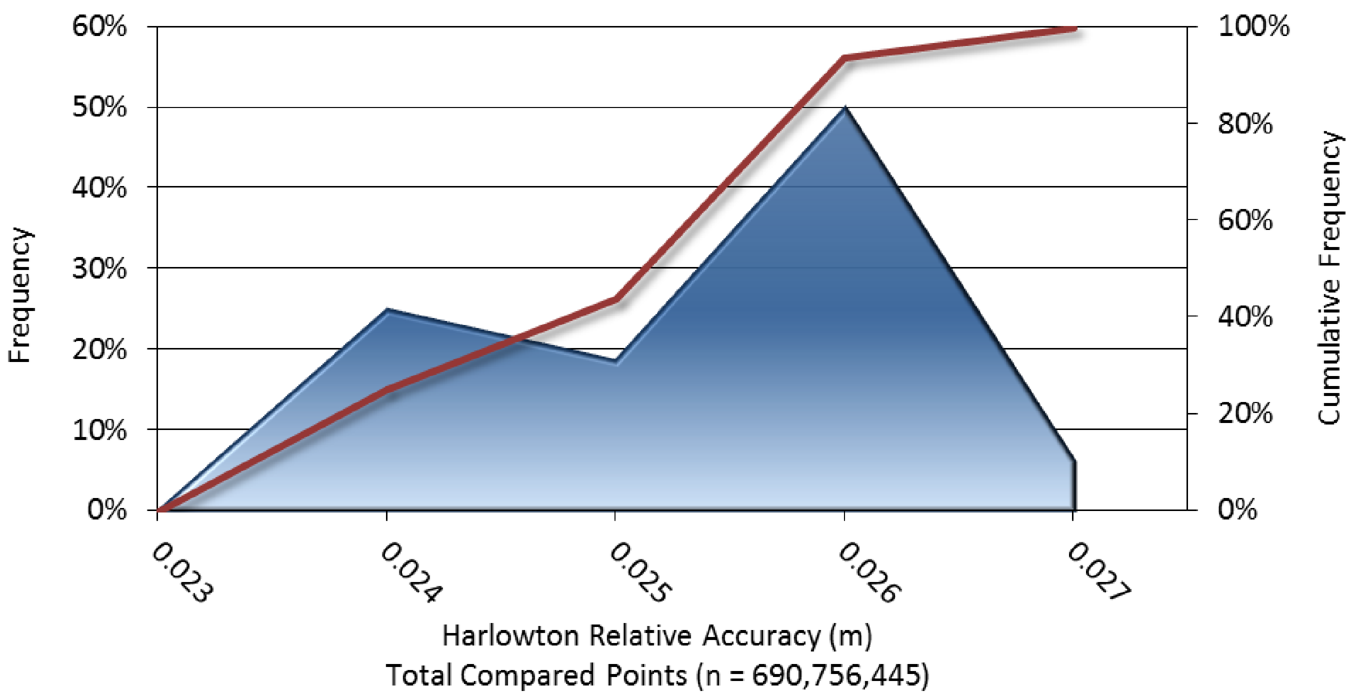


Figure 8: Frequency plot for relative vertical accuracy between flight lines

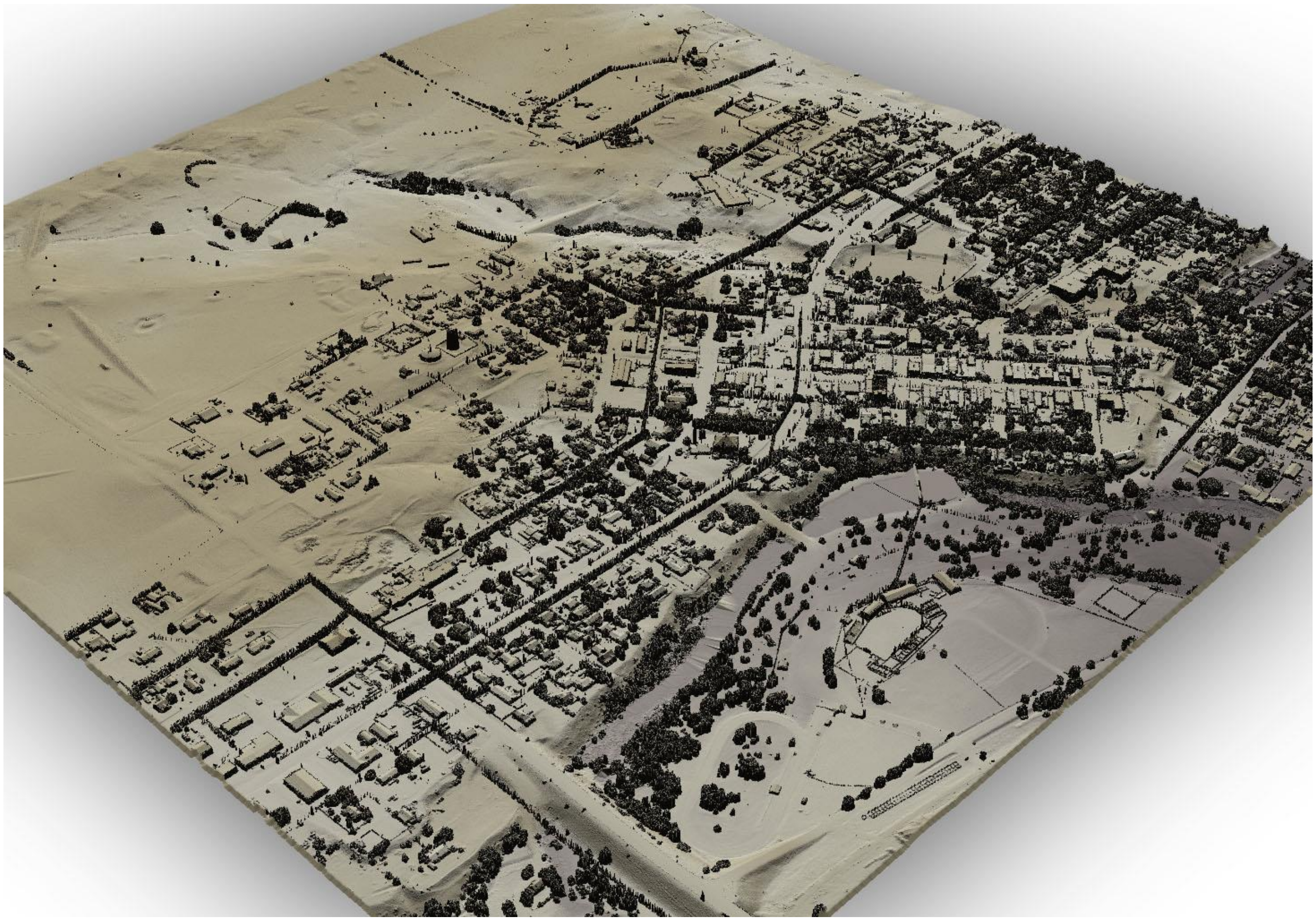


Figure 9: A view of downtown Harlowton, created from the gridded highest hit model colored by elevation.

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 * RMSE Absolute Deviation: Value for which the data are within two standard deviations (approximately 95th percentile) of a normally distributed data set, based on the FGDC standards for Fundamental Vertical Accuracy (FVA) reporting.

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 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, and 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; i.e., 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.

Digital Elevation Model (DEM): File or database made from surveyed points, containing elevation points over a contiguous area. Digital terrain models (DTM) and digital surface models (DSM) are types of DEMs. DTMs consist solely of the bare earth surface (ground points), while DSMs include information about all surfaces, including vegetation and man-made structures.

Intensity Values: The peak power ratio of the laser return to the emitted laser, calculated as a function of surface reflectivity.

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 in thousands of pulses per second (kHz).

Pulse Returns: For every laser pulse emitted, the number of wave forms (i.e., echos) reflected back to the sensor. Portions of the wave form that return first 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: A type of surveying 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.

Post-Processed Kinematic (PPK) Survey: GPS surveying is conducted with a GPS rover collecting concurrently with a GPS base station set up over a known monument. Differential corrections and precisions for the GNSS baselines are computed and applied after the fact during processing. 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.

Native LiDAR Density: The number of pulses emitted by the LiDAR system, commonly expressed as pulses per square meter.

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 was employed to maintain a constant above ground level (AGL). Laser horizontal errors are a function of flight altitude above ground (about 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 (i.e., intensity) 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 $\pm 14^{o}$ 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 13 nm at all times.

Ground Survey: Ground survey point accuracy (<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 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 nadir portion of one flight line coincides with the swath edge 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 have opposing directions. 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.