January 7, 2022
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Saint Mary Canal, Montana Lidar

Technical Data Report

Prepared For:

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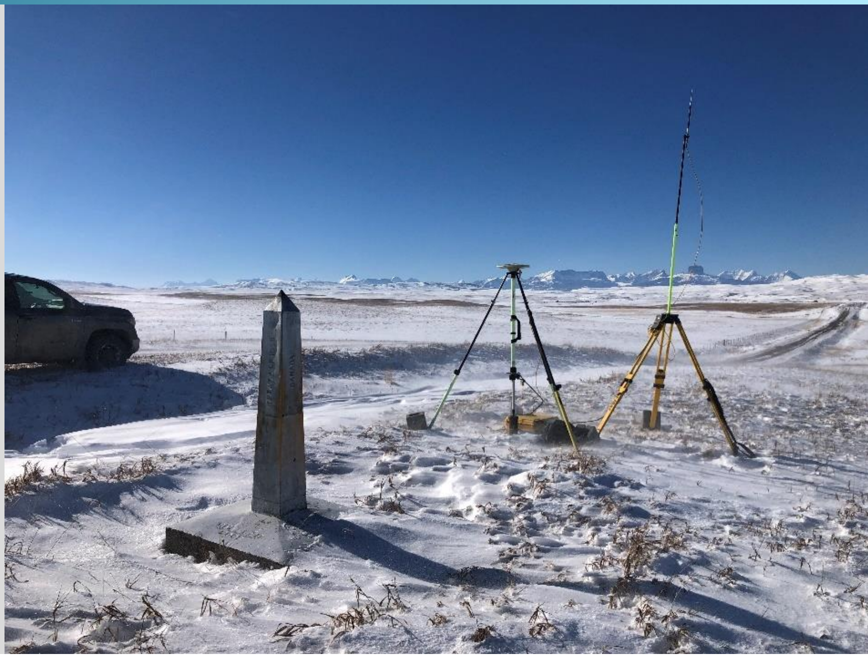
Cover Photo: A photo taken by NV5 acquisition staff showing a view looking south at the snowy fields and hills in the Saint Mary Canal site in Montana.

INTRODUCTION

This photo taken by NV5 Geospatial acquisition staff shows a view of the AB3812 Monument on the U.S. Canada border in the Saint Mary Canal site in Montana.



In September 2021, NV5 Geospatial (NV5) was contracted by Farmers Conservation Alliance (FCA) to collect Light Detection and Ranging (lidar) data in the fall of 2021 for the Saint Mary Canal site in Montana. Data were collected to aid FCA in assessing the topographic and geophysical properties of the study area to support irrigation districts with system modernization efforts. These efforts aim to increase irrigation efficiency, provide energy savings, conserve water, and potentially generate renewable power.

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 FCA 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 Saint Mary Canal site

Project Site	Contracted Acres	Buffered Acres	Acquisition Date	Data Type
Saint Mary Canal, Montana	3,627	4,722	10/21/2021	Topographic Lidar

Deliverable Products

Table 2: Products delivered to FCA for the Saint Mary Canal site

Saint Mary Canal Lidar Products Projection: Montana State Plane (2500MT) Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID18) Units: International Feet	
Points	LAS v 1.4 • All Classified Returns • Model Keypoints
Rasters	3.0 Foot ESRI Grids • Bare Earth Digital Elevation Model (DEM) • Highest Hit Digital Surface Model (DSM) 1.5 Foot GeoTiffs • Intensity Images
Vectors	Shapefiles (*.shp) • Area of Interest • Lidar Tile Index • Contours (0.5 foot)** Drawing Exchange Files (*.dxf) • Contours (0.5 foot)

**NV5 Supplied these files as a supplementary deliverable.

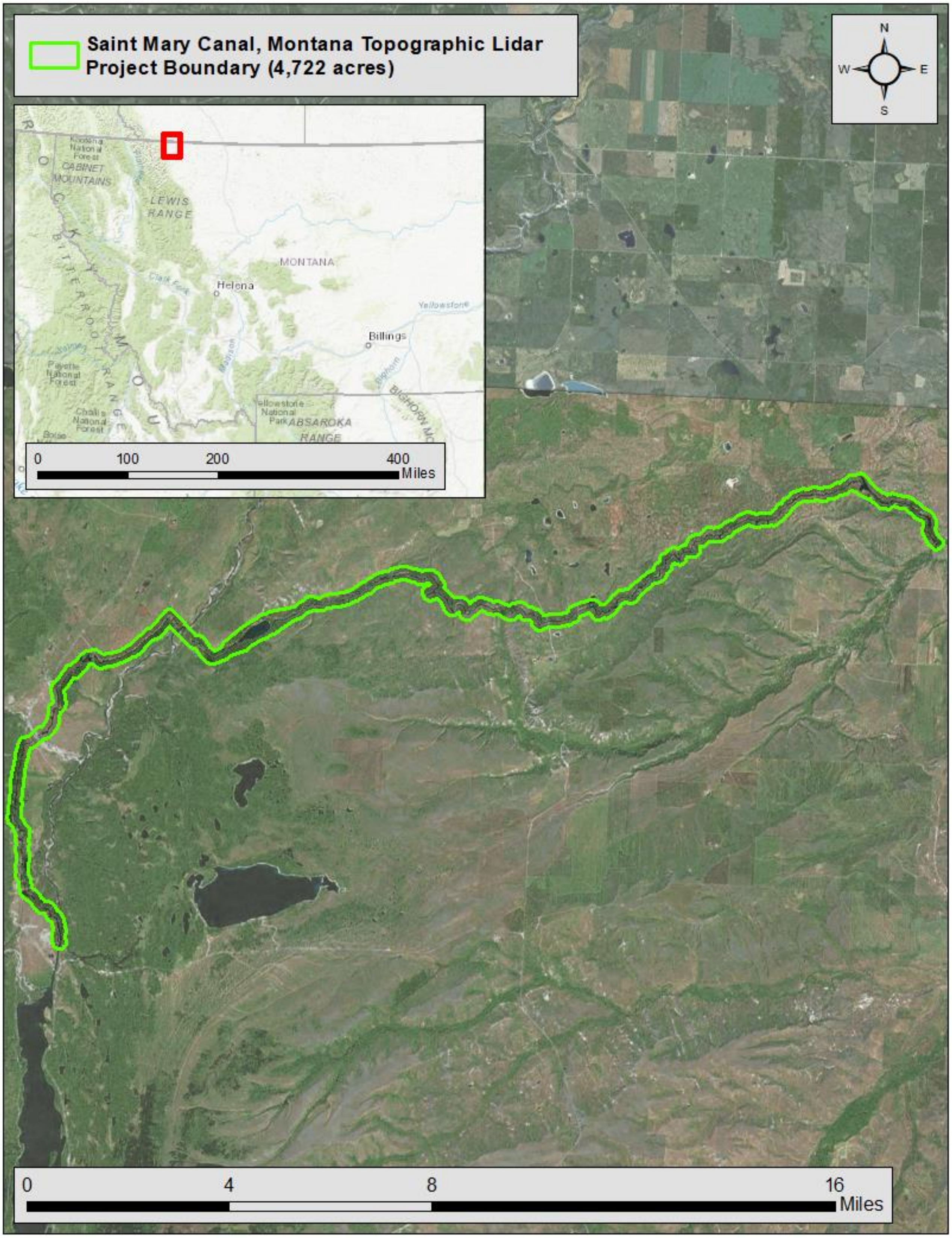
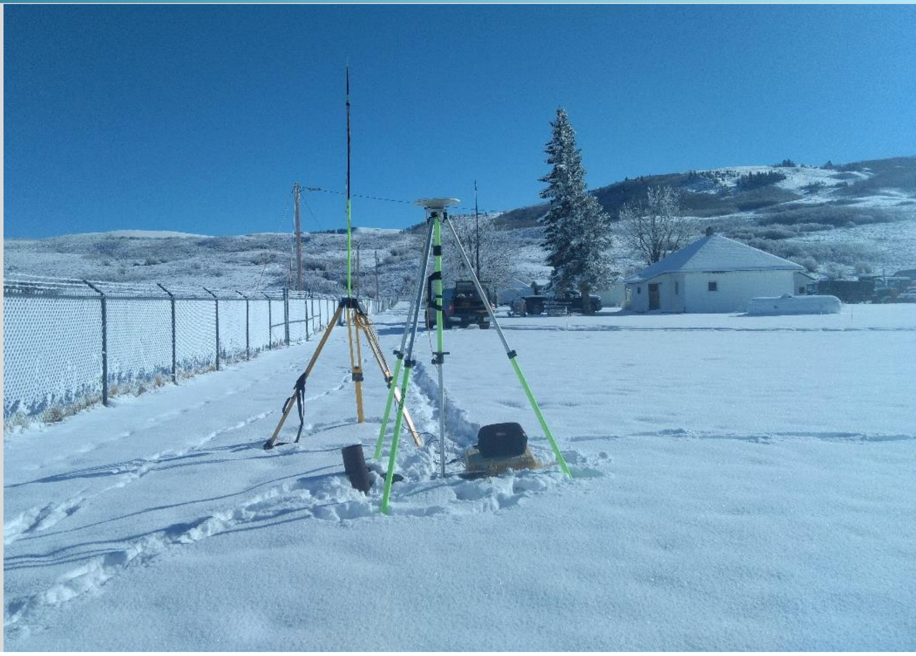


Figure 1: Location map of the Saint Mary Canal site in Montana

NV5 Geospatial's ground acquisition equipment set up in the Saint Mary Canal Lidar study area.



Planning

In preparation for data collection, NV5 Geospatial reviewed the project area and developed a specialized flight plan to ensure complete coverage of the Saint Mary Canal lidar study area at the target point density of ≥8.0 points/m^2 (0.74 points/ft^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. Lidar data was collected in snow free conditions and ground survey points were collected after on snow free surfaces or by clearing snow to the surface. In addition, logistical considerations including private property access, tribal lands access and potential air space restrictions were reviewed.

Airborne Lidar Survey

The lidar survey was accomplished using a Riegl VQ-1560ii-S system mounted in a Cessna Caravan. Table 3 summarizes the settings used to yield an average pulse density of ≥8 pulses/m^2 over the Saint Mary Canal project area. The Riegl VQ-1560ii-S laser system can record 45 measurements (returns) per pulse; however, a maximum of 15 returns can be stored due to LAS v1.4 file limitations. 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	October 21, 2021
Aircraft Used	Cessna Caravan
Sensor	Riegl
Laser	VQ-1560ii-S
Maximum Returns	9
Resolution/Density	Average 8 pulses/m^2
Nominal Pulse Spacing	0.35 m
Survey Altitude (AGL)	2,083 m
Survey speed	145 knots
Field of View	58.5º
Mirror Scan Rate	Uniform Point Spacing
Target Pulse Rate	872 kHz
Pulse Length	3.0 ns
Laser Pulse Footprint Diameter	48 cm
Central Wavelength	1064 nm
Pulse Mode	Multiple Times Around (MTA)
Beam Divergence	0.23 mrad
Swath Width	2,333 m
Swath Overlap	55%
Intensity	16-bit

Riegl VQ-1560ii-S lidar sensor

All areas were surveyed with an opposing flight line side-lap of ≥55% (≥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.

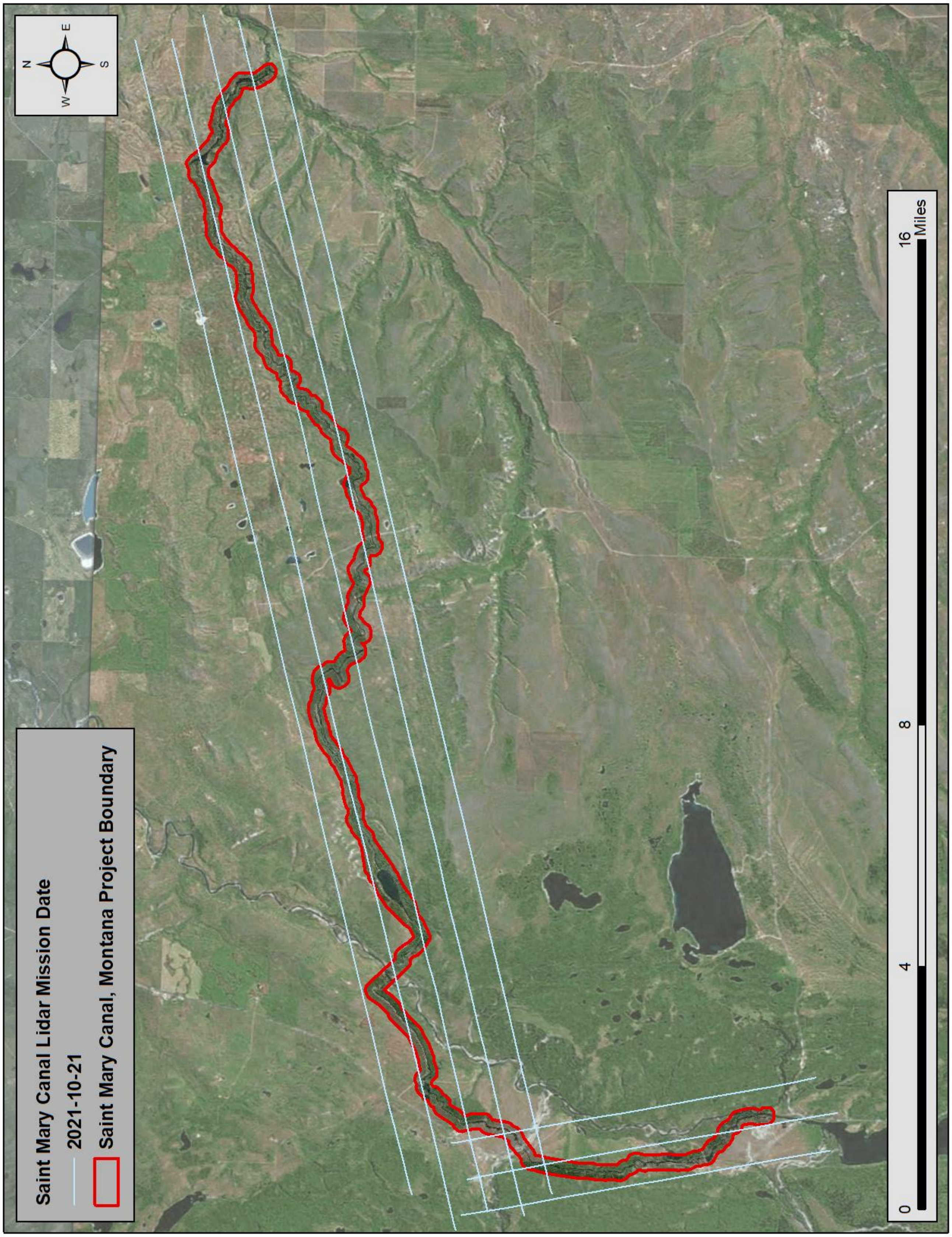


Figure 2: Saint Mary Canal flightline map

Ground Survey

Existing NGS Monument

Ground control surveys, including monumentation and ground survey points (GSPs) were conducted to support the airborne acquisition. Ground control data were used to geospatially correct the aircraft positional coordinate data and to perform quality assurance checks on final lidar data.

Base Stations

Base stations were utilized for collection of ground survey points using real time kinematic (RTK) and fast static (FS) survey techniques.

Monument locations were selected with consideration for satellite visibility, field crew safety, and optimal location for GSP coverage. NV5 Geospatial utilized two existing NGS monuments for the Saint Mary Canal Lidar project (Table 4, Figure 3). NV5 Geospatial's professional land surveyor, Steven J. Hyde (MTPLS#60192) oversaw and certified the ground survey and occupation of all monuments.

Table 4: Base station positions for the Saint Mary Canal acquisition. Coordinates are on the NAD83 (2011) datum, epoch 2010.00. UTM coordinates are in meters, zone 12N. Montana State Plane Coordinates (SPC) are in International Feet. Orthometric heights are derived using Geoid18.

Monument ID	Latitude UTM Northing (m) SPC Northing (ft)	Longitude UTM Easting (m) SPC Easting (ft)	Ellipsoid (m) Ortho Height (m) Ortho Height (ft)
AB3811	48° 56' 23.68774"	-113° 22' 21.02986"	1299.508
	5423489.181	326266.865	1314.234
	1732929.691	1038145.723	4311.790
AB3812	48° 59' 54.33032"	-113° 08' 29.14841"	1272.775
	5429490.180	343370.493	1287.695
	1751591.888	1094612.407	4224.720

NV5 Geospatial utilized static Global Navigation Satellite System (GNSS) data collected at 1 Hz recording frequency for each base station. During post-processing, the static GNSS 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.

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

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

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 is shown in Table 5.

Table 5: Federal Geographic Data Committee monument rating for network accuracy

Direction	Rating
1.96 * St Dev $_{NE}$:	0.050 m
1.96 * St Dev $_{z}$:	0.020 m

For the Saint Mary Canal Lidar project, the monument coordinates contributed no more than 5.6 cm of positional error to the geolocation of the final ground survey points and lidar, with 95% confidence.

Ground Survey Points (GSPs)

Ground survey points were collected using real time kinematic (RTK) and fast-static (FS) survey techniques. For RTK surveys, a roving receiver receives corrections from a nearby base station or Real-Time Network (RTN) via radio or cellular network, enabling rapid collection of points with relative errors less than 1.5 cm horizontal and 2.0 cm vertical. FS surveys compute these corrections during post-processing to achieve comparable accuracy. RTK surveys record data while stationary for at least five seconds, calculating the position using at least three one-second epochs. FS surveys record observations for up to fifteen minutes on each GSP in order to support longer baselines. 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. See Table 6 for Trimble unit specifications.

GSPs were collected in areas where good satellite visibility was achieved on paved roads and other hard surfaces such as gravel or packed dirt roads. GSP 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. 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 3). NV5 project management and ground survey staff worked with the Blackfoot tribe to gain access to tribal lands for the collection of additional ground survey points.

Table 6: NV5 Geospatial ground survey equipment identification

Receiver Model	Antenna	OPUS Antenna ID	Use
Trimble R7	Zephyr GNSS Geodetic Model 2 RoHS	TRM57971.00	Static
Trimble R12	Integrated Antenna	TRMR12	Rover

[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

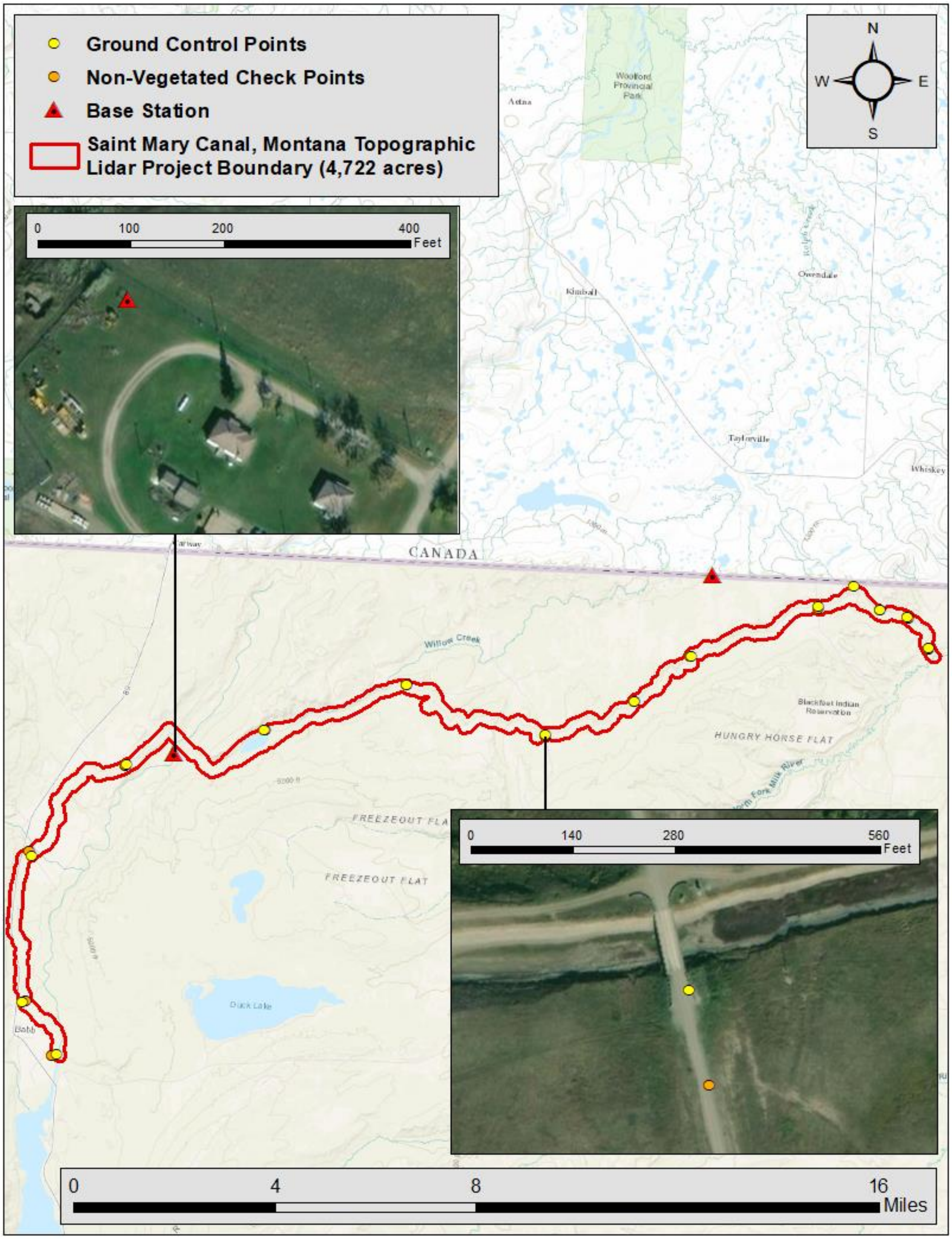


Figure 3: Ground survey location map

This 5 foot lidar cross section shows a view of the Saint Mary Canal landscape, colored by point classification.

Lidar Data

Upon completion of data acquisition, NV5 Geospatial 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 7). Processing methodologies were tailored for the landscape. Brief descriptions of these tasks are shown in Table 8.

Table 7: ASPRS LAS classification standards applied to the Saint Mary Canal dataset

Classification Number	Point Count	Classification Name	Classification Description
1	192,507,912	Default/Unclassified	Laser returns that are not included in the ground class, composed of vegetation and anthropogenic features
2	173,599,714	Ground	Laser returns that are determined to be ground using automated and manual cleaning algorithms
8	5,737,903	Model Key Points	Previously classified ground points, thinned using a spacing tolerance of 20 feet

Table 8: 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.	POSPac MMS v.8.5
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. 1.4) format. Convert data to orthometric elevations by applying a geoid correction.	RiWorld v.6.1.1 TerraMatch v.19
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.	BayesMap-StripAlign v.2.19
Import calibrated points into manageable blocks for editing	TerraScan v.19.005
Classify resulting data to ground and other client designated ASPRS classifications (Table 7). Assess statistical absolute accuracy via direct comparisons of ground classified points to ground control survey data.	TerraScan v.19.005 TerraModeler v.19.003
Generate bare earth models as triangulated surfaces. Generate highest hit models as a surface expression of all classified points. Export all surface models as ESRI GRIDs at a 3.0-foot pixel resolution.	LAS Product Creator 3.5 (NV5 Geospatial proprietary) ArcMap v. 10.3.1
Correct intensity values for variability and export intensity images as GeoTIFFs at a 1.5-foot pixel resolution.	LAS Product Creator 3.5 (NV5 Geospatial proprietary) ArcMap v. 10.3.1

Feature Extraction

Contours

Contour generation from lidar point data required a thinning operation in order to reduce contour sinuosity. The thinning operation reduced point density where topographic change is minimal (i.e., flat surfaces) while preserving resolution where topographic change was present. Model key points were selected from the ground model every 20 feet with the spacing decreased in regions with high surface curvature. Generation of model key points eliminated redundant detail in terrain representation, particularly in areas of low relief, and provided for a more manageable dataset. Contours were produced through TerraModeler by interpolating between the model key points at even elevation increments.

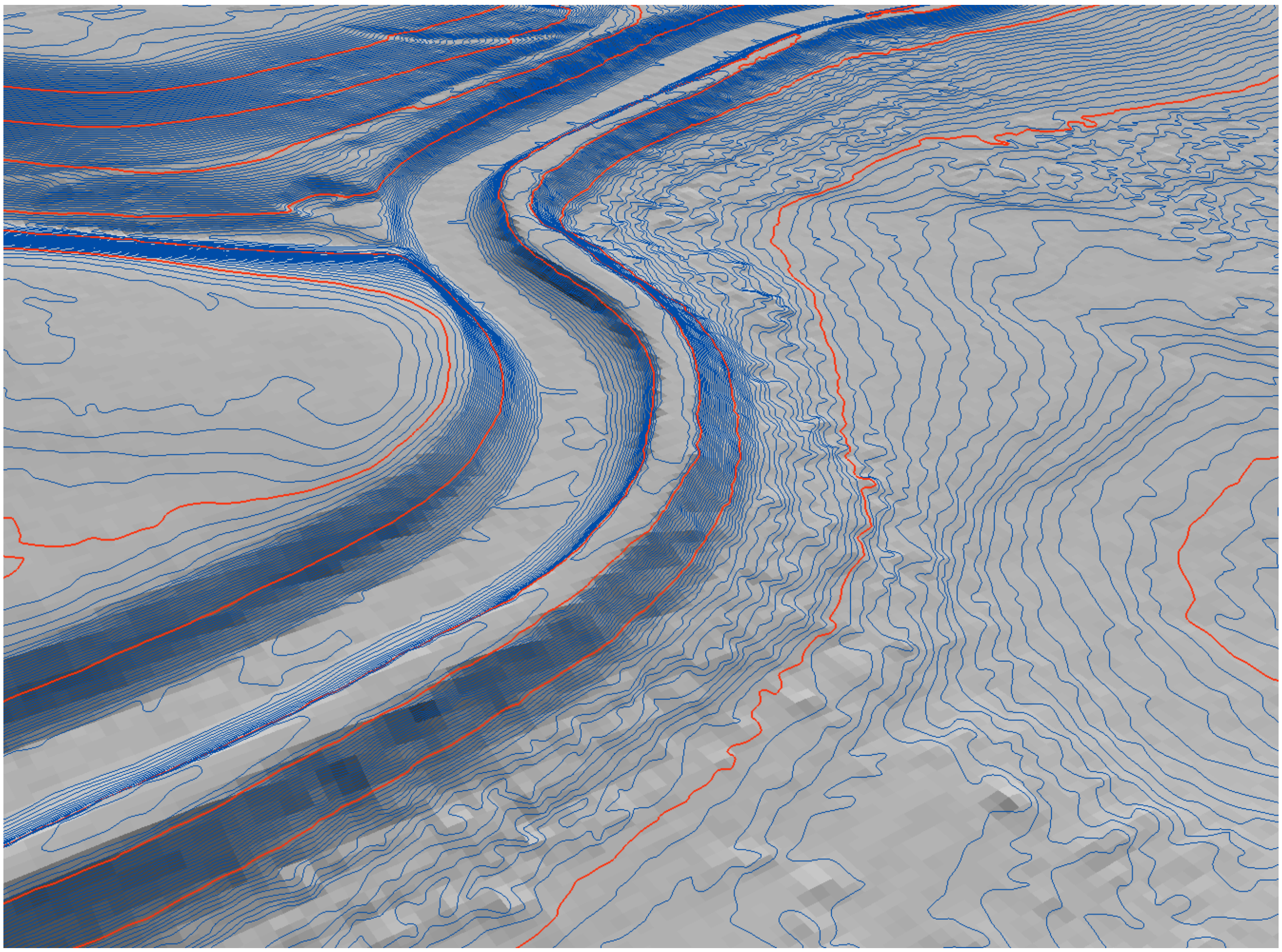
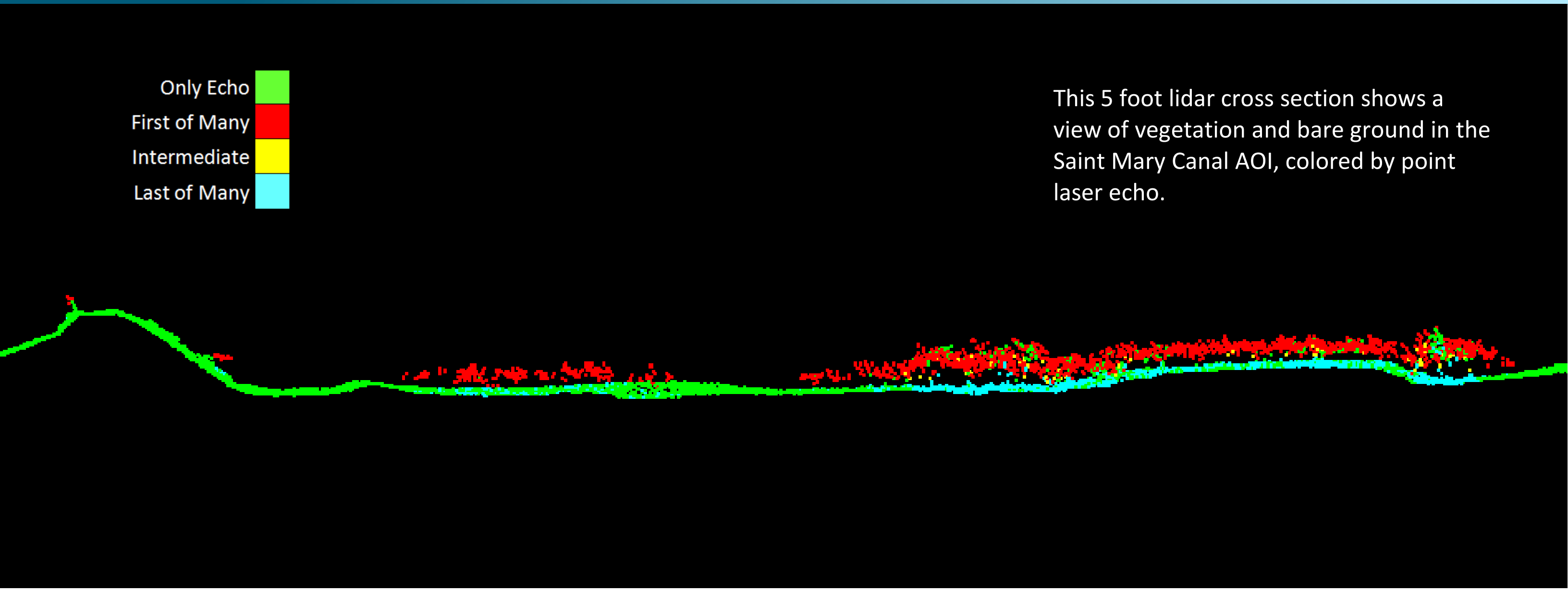


Figure 4: Contours draped over the Saint Mary Canal bare earth elevation model. Blue contours represent basic 0.5 foot intervals while the red contours represent major 10 foot intervals.



This 5 foot lidar cross section shows a view of vegetation and bare ground in the Saint Mary Canal AOI, colored by point laser echo.

Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m^2 (0.74 points/ft^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 Saint Mary Canal project was 1.59 points/ft^2 (17.12 points/m^2) while the average ground classified density was 0.85 points/ft^2 (9.12 points/m^2) (Table 9). 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 5 through Figure 8.

Table 9: Average lidar point densities

Classification	Point Density
First-Return	1.59 points/ft^2 17.12 points/m^2
Ground Classified	0.85 points/ft^2 9.12 points/m^2

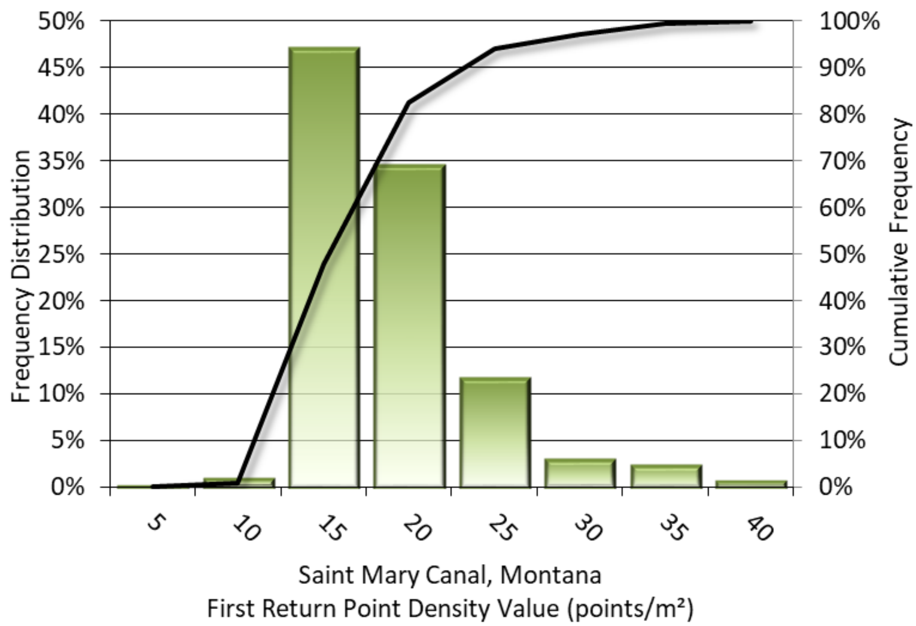


Figure 5: Frequency distribution of first return point density values per 100 x 100 m cell

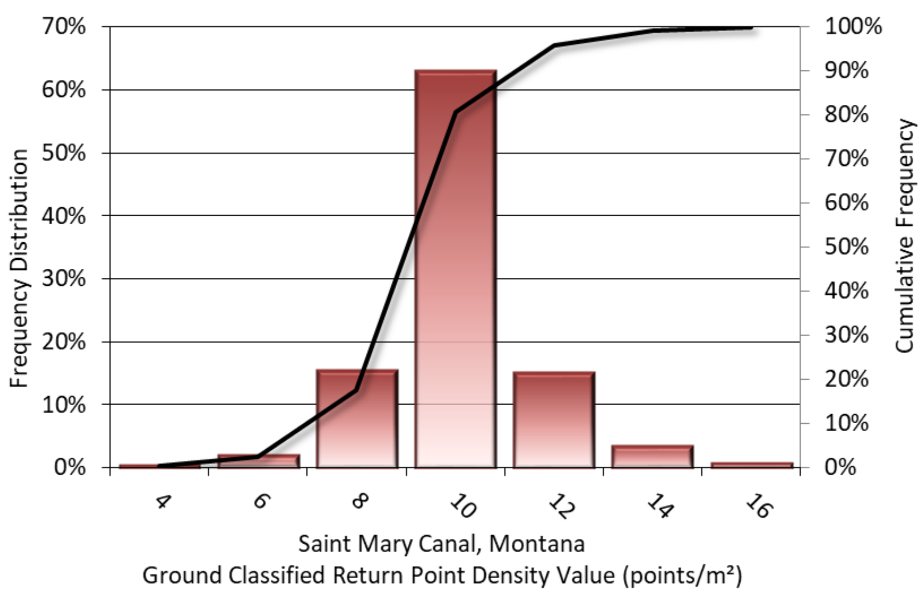


Figure 6: Frequency distribution of ground-classified return point density values per 100 x 100 m cell

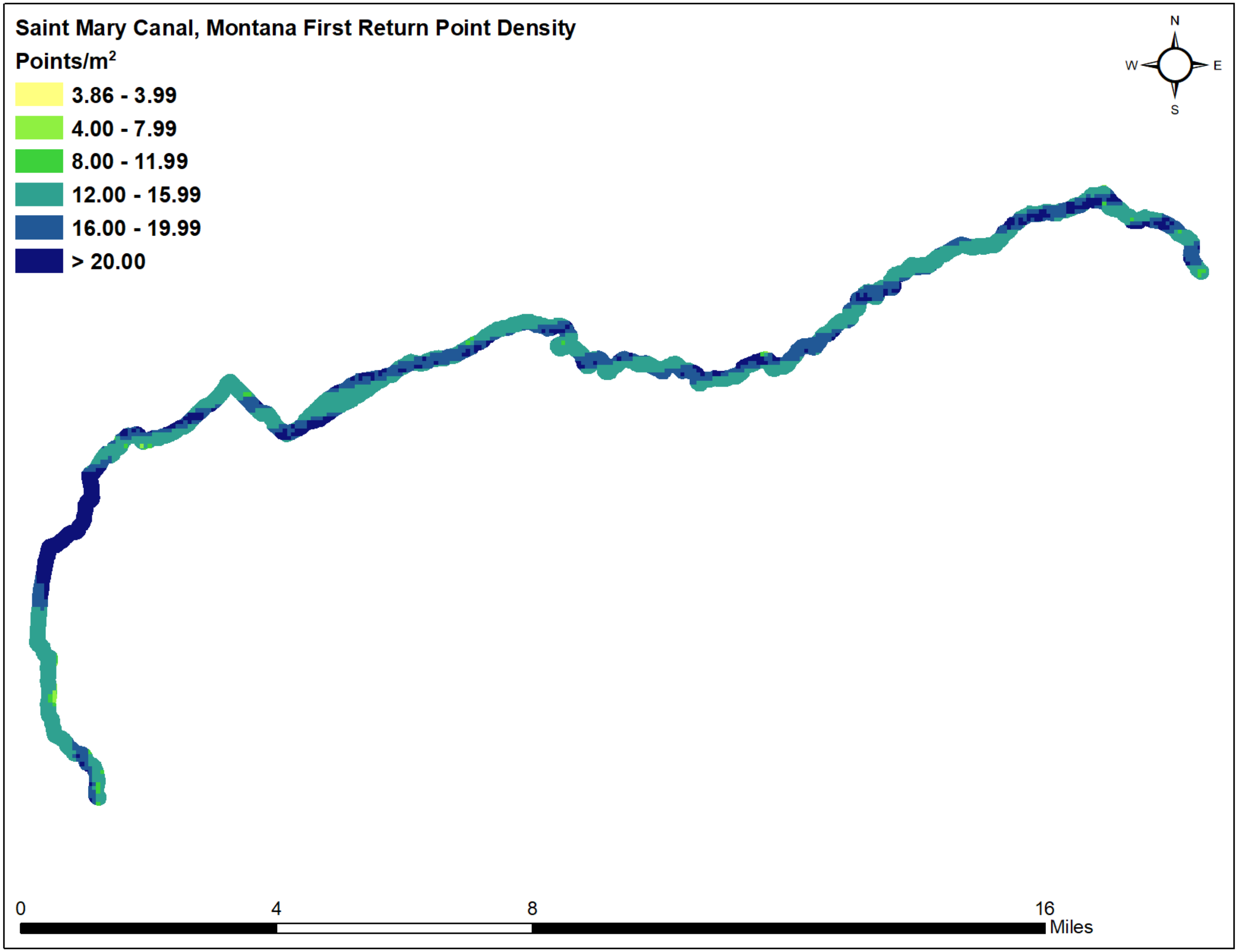


Figure 7: First return point density map for the Saint Mary Canal site (100 m x 100 m cells)

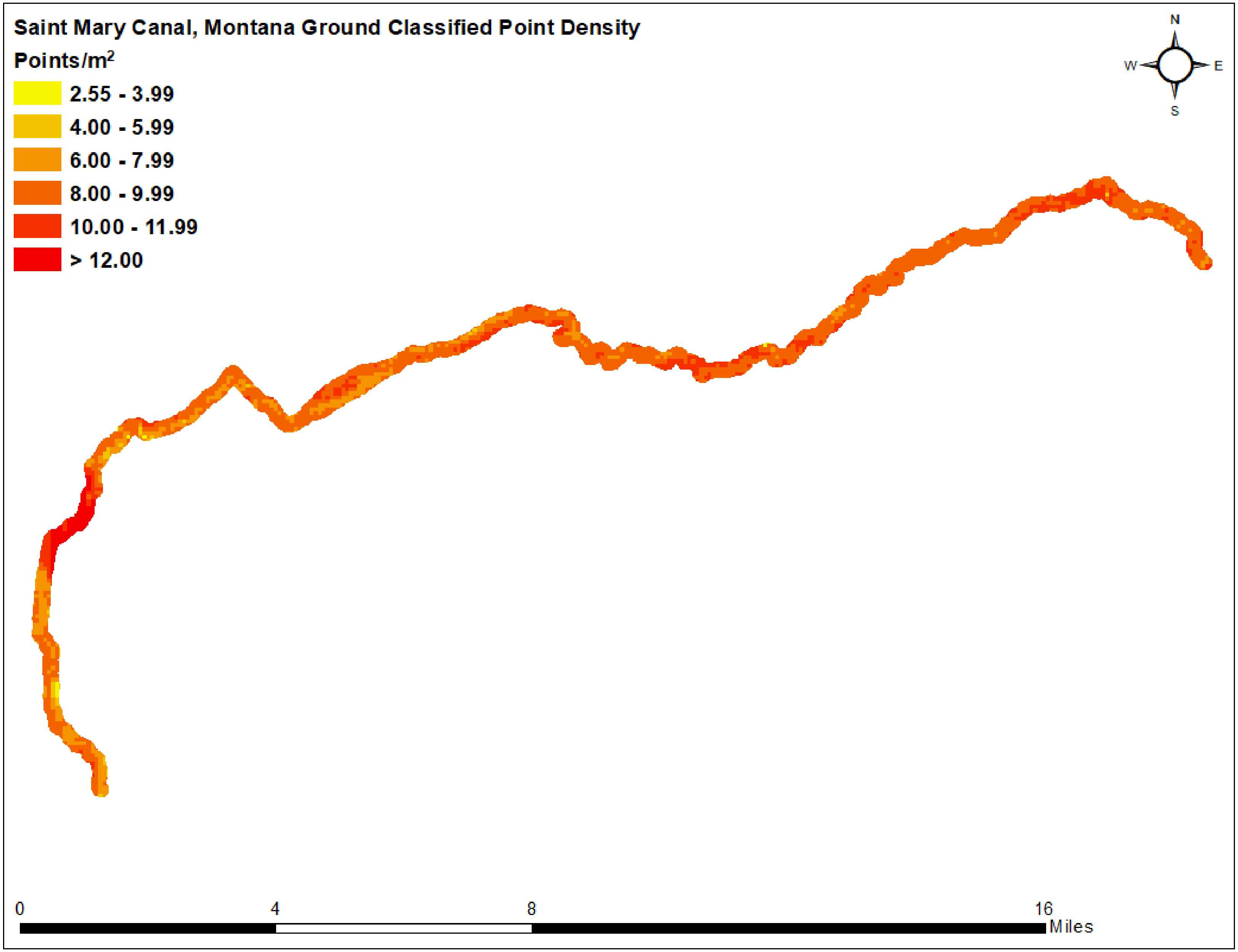


Figure 8: Ground point density map for the Saint Mary Canal site (100 m x 100 m cells)

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

Absolute accuracy was assessed using Non-Vegetated Vertical Accuracy (NVA) reporting designed to meet guidelines presented in the FGDC National Standard for Spatial Data Accuracy[3]. NVA compares known ground check point data that were withheld from the calibration and post-processing of the lidar point cloud to the triangulated surface generated by the classified lidar point cloud as well as the derived gridded bare earth DEM. NVA 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 10.

The mean and standard deviation (sigma σ) of divergence of the ground surface model from quality assurance 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 Saint Mary Canal survey, 14 ground check points were withheld from the calibration and post processing of the lidar point cloud, with resulting non-vegetated vertical accuracy of 0.151 feet (0.046 meters) as compared to classified LAS, and 0.159 feet (0.048 meters) as compared to the bare earth DEM, with 95% confidence (Figure 9, Figure 10).

NV5 Geospatial also assessed absolute accuracy using 14 ground control points. Although these points were used in the calibration and post-processing of the lidar point cloud, they still provide a good indication of the overall accuracy of the lidar dataset, and therefore have been provided in Table 10 and Figure 11.

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[3] Federal Geographic Data Committee, ASPRS POSITIONAL ACCURACY STANDARDS FOR DIGITAL GEOSPATIAL DATA EDITION 1, Version 1.0, NOVEMBER 2014. https://www.asprs.org/a/society/committees/standards/Positional_Accuracy_Standards.pdf.

Table 10: Absolute accuracy results

Absolute Vertical Accuracy			
	NVA, as compared to classified LAS	**NVA, as compared to bare earth DEM**	**Ground Control Points**
Sample	14 points	14 points	14 points
95% Confidence (1.96*RMSE)	0.151 ft 0.046 m	0.159 ft 0.048 m	0.148 ft 0.045 m
Average	-0.016 ft -0.005 m	-0.054 ft -0.016 m	-0.009 ft -0.003 m
Median	-0.008 ft -0.003 m	-0.059 ft -0.018 m	-0.008 ft -0.003 m
RMSE	0.077 ft 0.023 m	0.081 ft 0.025 m	0.076 ft 0.023 m
Standard Deviation (1σ)	0.078 ft 0.024 m	0.063 ft 0.019 m	0.078 ft 0.024 m

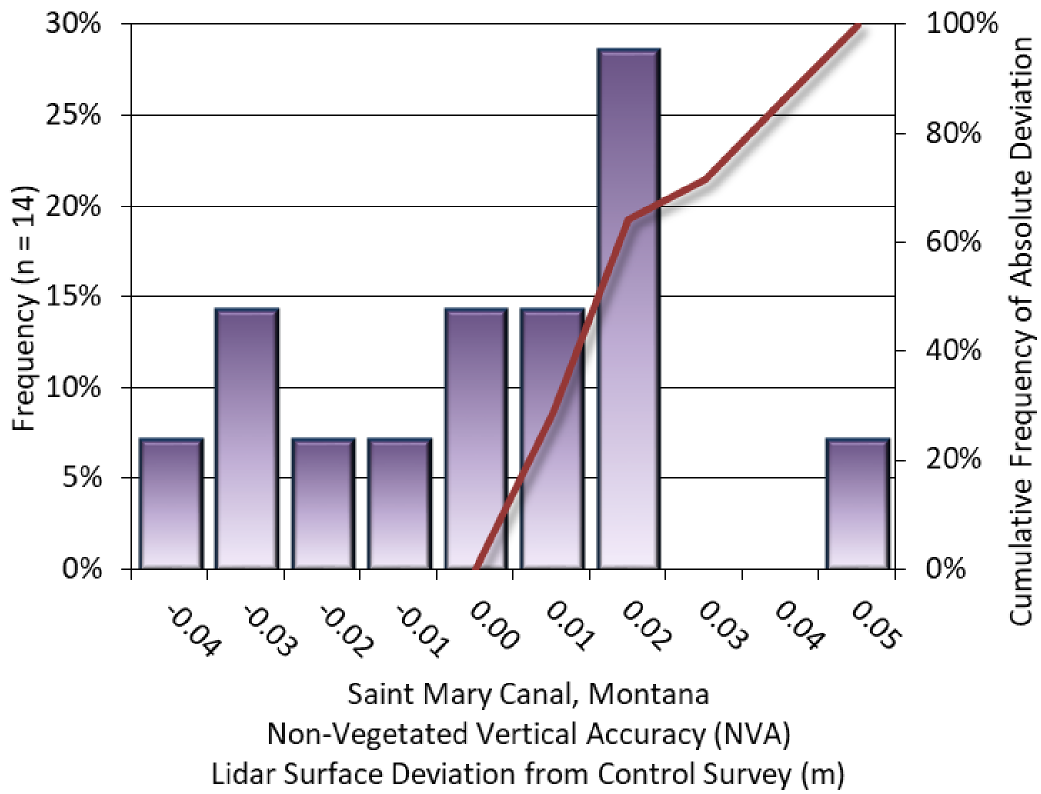

Figure 9: Frequency histogram for lidar classified LAS deviation from ground check point values (NVA)

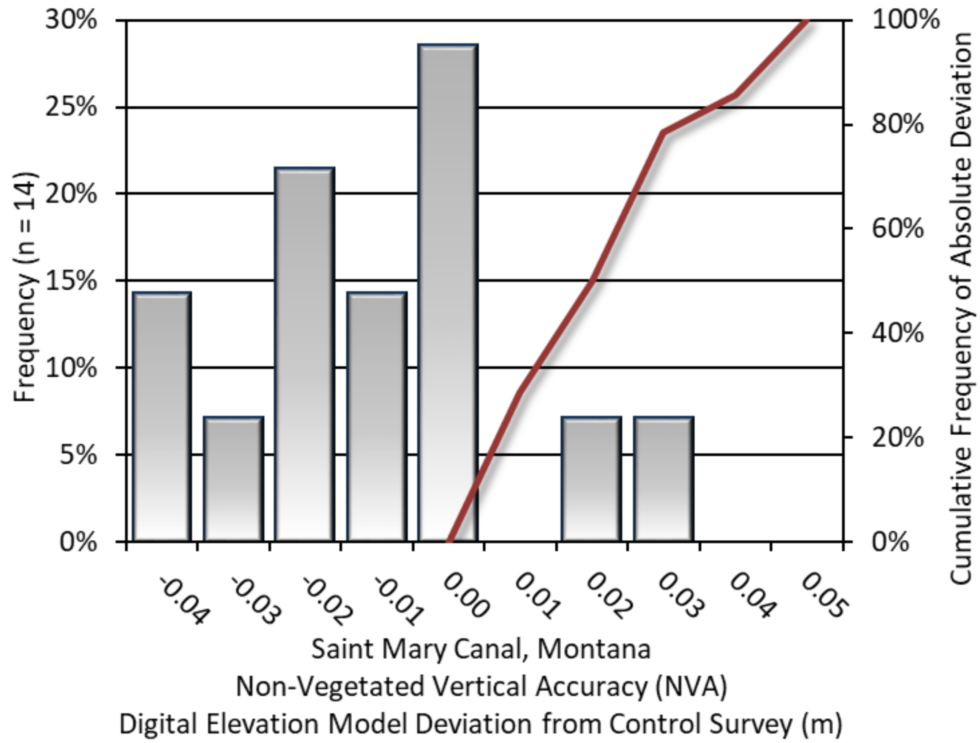

Figure 10: Frequency histogram for the lidar bare earth DEM surface deviation from ground check point values (NVA)

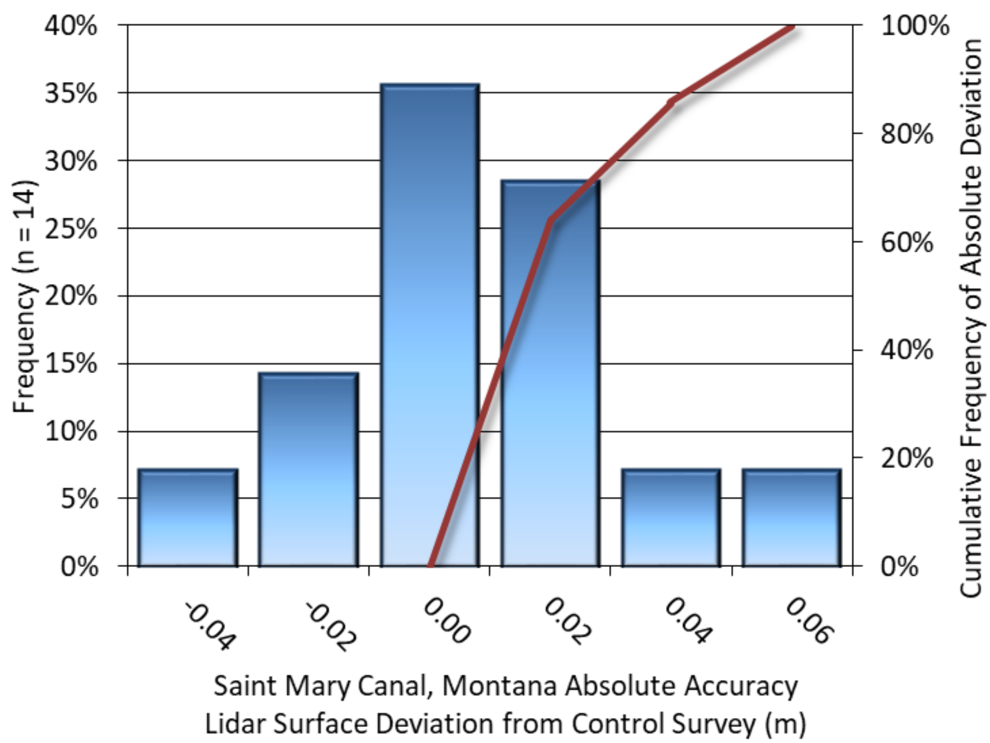

Figure 11: Frequency histogram the for lidar surface deviation from ground control point values

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 Saint Mary Canal Lidar project was 0.062 feet (0.019 meters) (Table 11, Figure 12).

Table 11: Relative accuracy results

Relative Accuracy	
Sample	8 flight line surfaces
Average	0.062 ft 0.019 m
Median	0.062 ft 0.019 m
RMSE	0.063 ft 0.019 m
Standard Deviation (1σ)	0.004 ft 0.001 m
1.96σ	0.008 ft 0.002 m

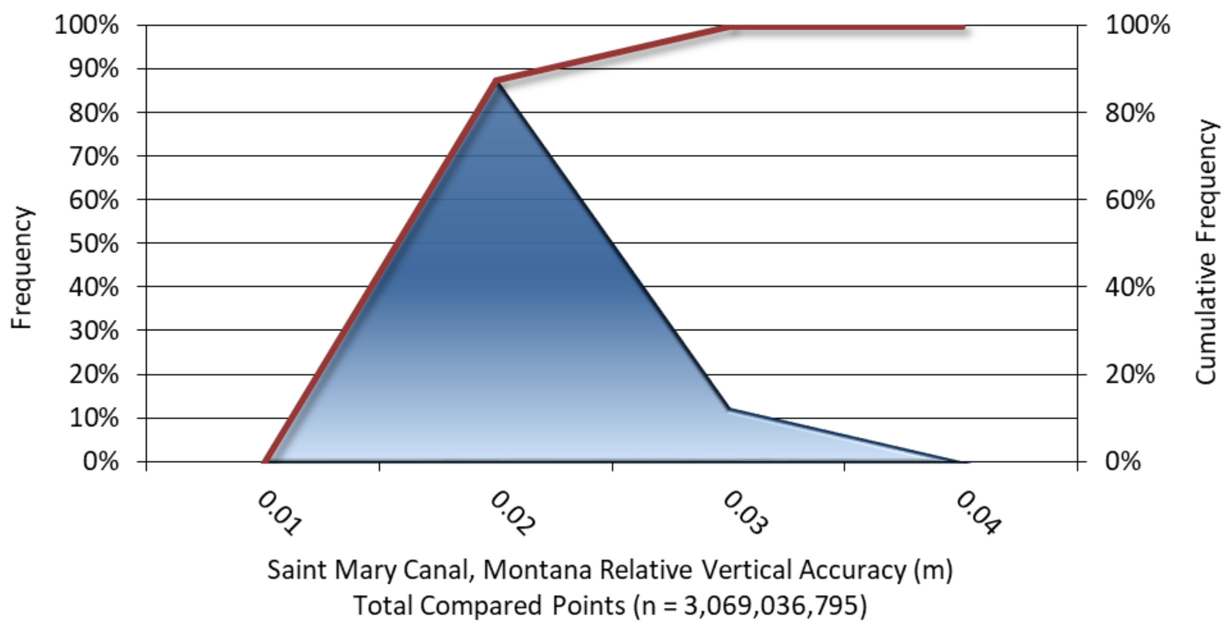

Figure 12: Frequency plot for relative vertical accuracy between flight lines

Lidar Horizontal Accuracy

Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95 percent of the time. Based on a flying altitude of 2,083 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.019 meters, this project was produced to meet 0.747 feet (0.228 m) horizontal accuracy at the 95% confidence level.

Table 12: Horizontal Accuracy

Horizontal Accuracy	
$RMSE_r$	0.431 ft 0.131 m
ACC_r	0.747 ft 0.228 m

CERTIFICATIONS

NV5 Geospatial provided lidar services for the Saint Mary Canal project as described in this report.

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

Mar 7, 2022

Steven Miller
Project Manager
NV5 Geospatial

I, Steven J. Hyde, PLS, being duly registered as a Professional Land Surveyor in and by the state of Montana, hereby certify that the methodologies, static GNSS occupations used during airborne flights, and ground survey point collection were performed using commonly accepted Standard Practices. Field work conducted for this report was conducted between October 21 and November 1, 2021.

Accuracy statistics shown in the Accuracy Section of this Report have been reviewed by me and found to meet the "National Standard for Spatial Data Accuracy".

MONTANA
STEVEN J
HYDE
No. 60192 LS
3/3/22
LICENSED
PROF. LAND SURVEYOR

Steven J. Hyde
Professional Land Surveyor
NV5 Geospatial

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 Non-vegetated Vertical Accuracy (NVA) 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., echoes) 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 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 ±29.25^{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.