Lidar Mapping Report
for the U.S. Geological Survey

Contractor: Woolpert Inc.
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Contract : 140G0221D0013
Task Order: 140G0222F0098
Project Name: MN Central Miss River B22
Project ID: 230951
Work Name: MN Central Miss River 4 B22
Work Unit ID: 300158

U.S. Geological Survey
tnm_help@usgs.gov

WOOLPERT

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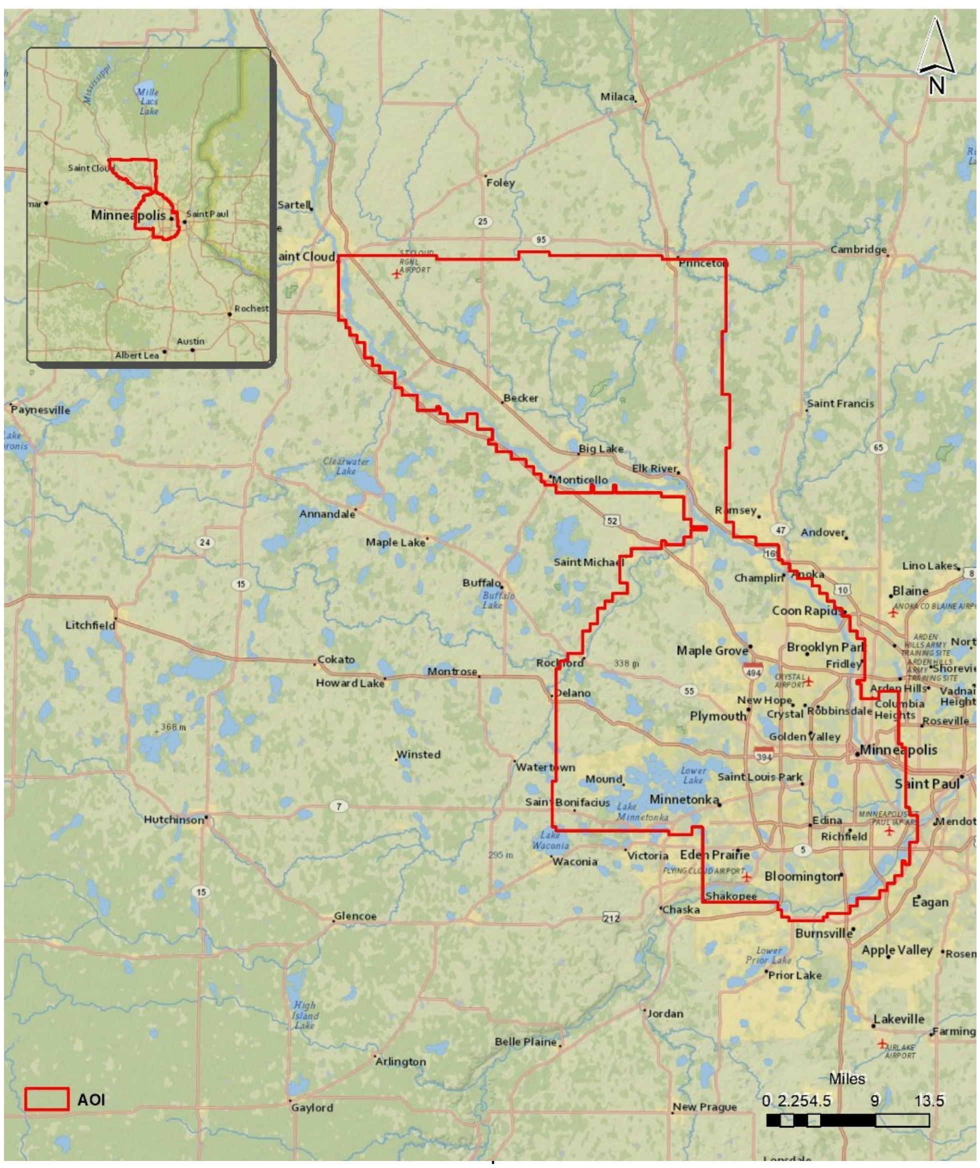
1. Overview

1.1. Description

MN_Central_Mississippi, 300158 is part of Task order 140G0222F0098.

This Lidar Mapping Report will cover the acquisition, processing, and derivative products of Work Unit 300158. Lidar data was collected to an aggregate nominal pulse spacing (ANPS) of ≤0.23 and 30-points per square meter (ppsm) covering 1,199 square miles in Central Minnesota to meet USGS Quality Level 1 standards. In addition to high density lidar data acquisition, new horizontal/vertical survey data was collected to support lidar data production. This work unit was acquired and processed by Woolpert GPSC4 team member NV5, under supervision by Woolpert.

Figure 1.1.1 – MN_CentralMissRiver_4_B22



1.2. Purpose

This project will support the 3DEP mission and the Natural Resources Conservation Service (NRCS) high-resolution elevation enterprise program.

1.3. Specifications

Data and reporting for this task order were acquired and produced to meet the "*USGS Lidar Base Specification* v2021 Revision A", and the American Society of Photogrammetry and Remote Sensing (ASPRS) "*Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1.0)*".

1.4. Spatial Reference

Geospatial data products were produced using the following spatial data reference system:

- Horizontal Datum: NAD83 (2011)
- Horizontal Projection: UTM 15N
- Horizontal Units: Meters
- Horizontal EPSG Code: 6344
- Vertical Datum: NAVD88
- Geoid Model: 18
- Vertical Units: Meters
- Height Type: Orthometric

1.5. Task Order Deliverables

All data products produced as part of this task order are listed below. All tiled deliverables had a tile size of 500-meters x 500-meters. Tiles are named in accordance with the MN Statewide Tiling Index.

1.5.1. Lidar Data

- Classified lidar point cloud data in compressed LAZ format:
  - Class 1 – Default / Processed, but not Classified
  - Class 2 – Bare Earth Ground
  - Class 7 – Low Noise
  - Class 9 – Water
  - Class 17 – Bridge Decks
  - Class 18 – High Noise
  - Class 20 – Ignored Ground
- Breaklines used for hydro-flattening:
  - Breaklines as PolylineZ features in Esri geodatabase format
- Hydro-flattened bare earth digital elevation model (DEM): 0.5-meter pixel size, 32-bit floating-point with no bridges or overpass structures, in GeoTIFF format
- Intensity imagery: 0.5-meter pixel size, 8-bit, 256 gray-scale (linear rescaling from 16-bit intensity) in GeoTIFF format

1.5.2. Spatial Metadata

- Data extent: Esri .shp format
- Swath polygons: Georeferenced, polygonal representation of the detailed extents of each lidar swath as polygon feature class in an Esri file geodatabase format
- Maximum Surface Height Raster: 1-meter pixel size, 32-bit floating-point, GeoTIFF format
- Swath separation images: 1-meter pixel size, GeoTIFF format.

1.6. Flight Planning

Flight planning was based on the unique project requirements and characteristics of the project site. The basis of planning included: required accuracies, type of development, amount / type of vegetation within project area, required data posting, and potential altitude restrictions for flights in project vicinity.

Detailed project flight planning calculations were performed for the project using RiPARAMETER planning software.

1.7. Lidar Sensor Information

Aerial lidar data was acquired using the Riegl VQ1560ii and VQ780ii lidar sensor systems.

1.7.1. Riegl VQ780ii Sensor Specifications

- Operating Altitude: 1,050 m AGL at 10% reflective target
- Maximum Measurement Rate: 2000-kHz
- Scan Angle : 30°-60°
- Scan Width: Up to 70% of flight altitude
- Scan Frequency: 150 kHz up to 2 MHz, selectable in steps of less than 1%
- Pulse Mode(s): Up to 35 pulses in air

1.7.2. Riegl VQ780ii Laser Specifications

- Laser Beam Divergence: 0.18-mrad (1/e)
- Laser Classification: Class 3B laser product

1.7.3. Riegl VQ780ii Accuracy

- Range Resolution: < 1 cm RMS
- Elevation Accuracy: < 5-cm 1 σ
- Horizontal Accuracy: < 13-cm 1 σ

1.7.4. Riegl VQ780ii Physical Specifications

- Scanner size: 425 mm x 212 mm x 331 mm
    - Scanner weight: 20-kg
    - Control Electronics size: 45 W x 47 D x 25 H-cm
    - Control Electronics weight: 33-kg
    - Scanner operating temperature: -5 – 40°C cabin-side temperature
    - Control Electronics operating temperature: -5 – 40°C
- Flight Management: RiPARAMETER

- Power Consumption: 18-32 VDC/ typ. 160 W

1.7.5. Riegl VQ1560ii Sensor Specifications

- Operating Altitude: 1,700 – 3,900-m AGL at 20% reflective target
- Maximum Measurement Rate: 55 kg without any camera but including a typical IMU/GNSS unit
- Scan Angle : 60° total per channel, resulting in an effective FOV of 58° Scan Width: Up to 70% of flight altitude
- Scan Frequency: 40-600 lines/sec
- Pulse Mode(s): Up to 45 pulses in air

1.7.6. Riegl VQ1560ii Laser Specifications

- Laser Beam Divergence: 0.17-mrad (1/e)
- Laser Classification: Class 3B laser product

1.7.7. Riegl VQ1560ii Accuracy

- Range Resolution: < 1 cm RMS
- Elevation Accuracy: < 5-cm 1 σ
- Horizontal Accuracy: < 13-cm 1 σ

1.7.8. Riegl VQ1560ii Physical Specifications

- Scanner size: max. 550 W, depending on integrated optional components, 524 mm x 780 mm (without flange mounted carrying handles), approx. 55 kg without any camera but including a typical IMU/GNSS unit, approx.
    - Scanner weight: 55 kg without any camera but including a typical IMU/GNSS unit
    - Control Electronics size: 45 W x 47 D x 25 H-cm
    - Control Electronics weight: 33-kg
    - Scanner operating temperature: -5 – +35°C/-10° up to +50° C
    - Control Electronics operating temperature: -5 – +35°C/-10° up to +50° C
- Flight Management: RiPARAMETER
- Power Consumption: 20-32 VDC/typ. 370 W

1.8. Planned Flight Specifications

Flight plans were created using RiPARAMETER. Aerial lidar data was acquired for this project using the following lidar sensor systems:

- SN3061(Riegl VQ1560ii), SN3546 (Riegl VQ1560ii), and SN7277 (Riegl VQ780ii)

The following settings for SN3061 (Riegl VQ 1560ii-s) and SN3546 (Riegl VQ1560ii-S) were used:

- Maximum Number of Returns: 15
- Nominal Point Spacing: 0.21-m
- Nominal Point Density: 30 ppsm
- Flying Height Above Ground Level: 910-m
- Flight Speed: 140-knots
- Scan Angle: 29.5°
- Scan Rate Used: 256 lps
- Pulse Rate Used: 4000-kHz
- Multi-Pulse in Air: Enabled
- Overlap: Minimum 20%

The following settings for SN7277 (Riegl VQ780ii-S) were used:

- Maximum Number of Returns: 15
- Aggregate Point Spacing: 0.23-m
- Aggregate Point Density: 30 ppsm
- Flying Height Above Ground Level: 1,050-m
- Flight Speed: 120-knots
- Scan Angle: 30°
- Scan Rate Used: 256 lps
- Pulse Rate Used: 2000-kHz
- Multi-Pulse in Air: Enabled
- Overlap: Minimum 60%

1.9. Timeline

Lidar data was collected from May 4, 2022, through May 24, 2022. A total of 151 individual flight lines were collected. Flight logs are contained in Attachment 1: Flight Logs.

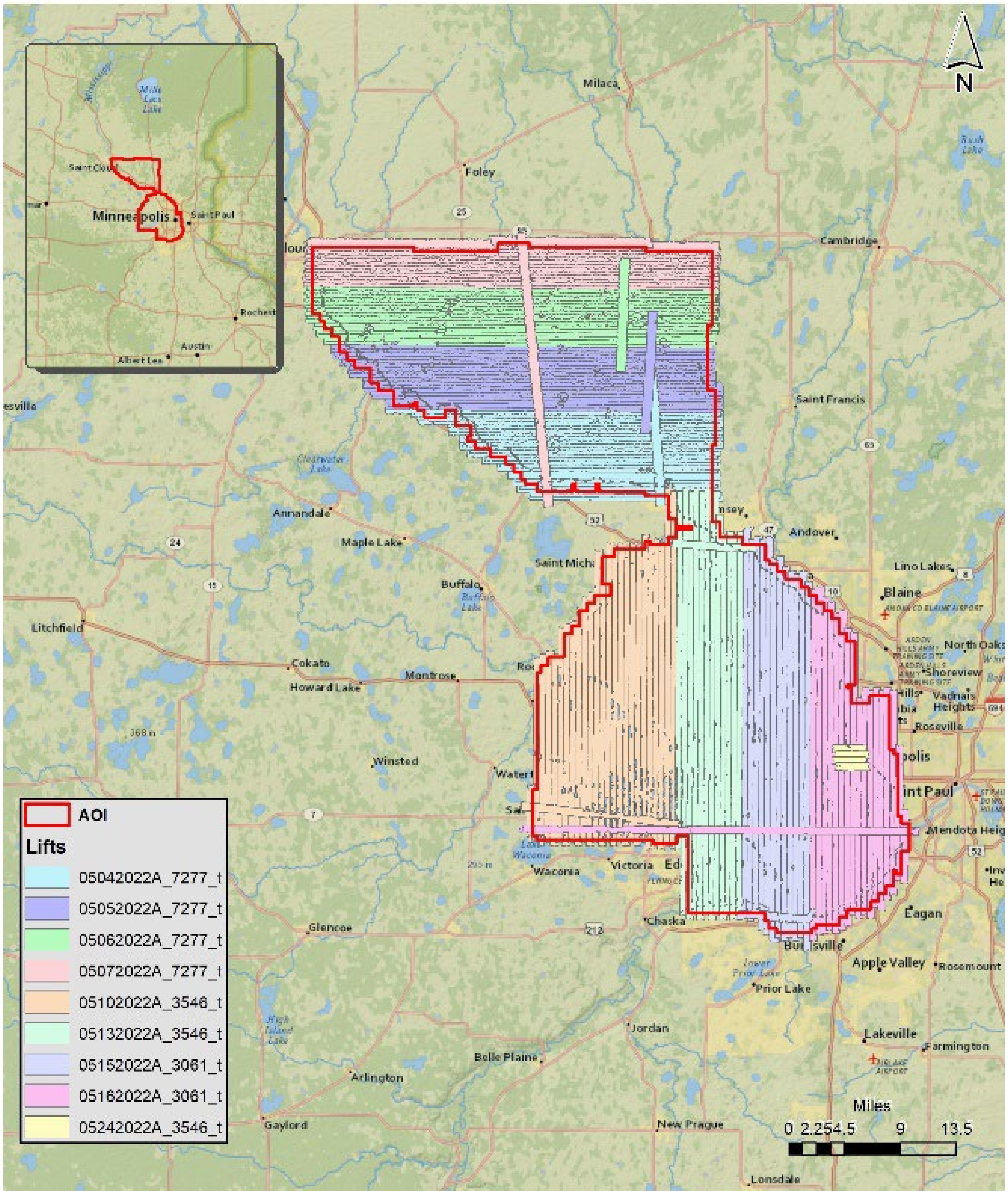
1.10. GNSS and IMU Equipment

Prior to mobilizing to the project site, flight crews coordinated with required air traffic control personnel to ensure airspace access. Crews were on-site, operating a Global Navigation Satellite System (GNSS) Base Station for airborne GPS support.

Flight navigation during acquisition was performed using flight management software. The pilots are skilled at maintaining their planned trajectory, while holding the aircraft steady and level. If atmospheric conditions were such that the trajectory, ground speed, roll, pitch and/or heading could not be properly maintained, the mission was aborted until suitable conditions occur.

GPS/IMU graphics are contained in Attachment 2: GPS IMU Images.

Figure 2.5.1. Flight Coverage by Lift



1.11. Acquisition Quality Assurance

A combination of off-the-shelf and proprietary software packages are used to ensure that all collected data meets the USGS LIDAR Base Specification. Each mission is typically shipped back to the office with 2-3 days of collection and the data review is prioritized to be completed within a week of the acquisition date of each mission. Our FOCUS tools are used as a preliminary check that the data meets the requirements for density, spatial distribution, no unnecessary data voids, and no noise. The overall quality of the processing solutions calculated during the POSPac processing is reviewed to be consistent with the needed accuracy specification outlined in project tasking. If there are issues found during the mission review, then these are brought to the attention of Acquisition to schedule a re-flight at the earliest available window. At the completion of the automated checks on the mission data are completed, a manual review of the dataset is completed. This, more granular, look at the data is to ensure that the automated routines didn't miss any gross errors or have masked any data voids that might be present in the dataset. Final acceptance of the mission is then sent onto Acquisition to confirm a successful flight. The final SBET reporting, as well as the accepted FOCUS on Flight report is maintained to ensure compliance with project specifications.

2. Processing

2.1. Processing Summary

Applanix + POSPac software was used for post-processing of airborne GPS and inertial data (IMU), which is critical to the positioning and orientation of the lidar sensor during all flights. Applanix POSPac combines aircraft raw trajectory data with stationary GPS base station data yielding a "Smoothed Best Estimate Trajectory" (SBET) necessary for additional post processing software to develop the resulting geo-referenced point cloud from the lidar missions.

During the sensor trajectory processing (combining GPS & IMU datasets) certain statistical graphs and tables are generated within the Applanix POSPac processing environment which are commonly used as indicators of processing stability and accuracy. This data for analysis include: max horizontal / vertical GPS variance, separation plot, altitude plot, PDOP plot, base station baseline length, processing mode, number of satellite vehicles, and mission trajectory.

Kinematic corrections for the aircraft position were resolved using aircraft GPS and static ground GPS (1-Hz) for each geodetic control (base station) for three subsystems: inertial measurement unit (IMU), sensor orientation information, and airborne GPS data.

Post-processing of the IMU system data and aircraft position with attitude data was completed to compute an optimally accurate and blended navigation solution based on Kalman filtering technology, or the smoothed best estimate of trajectory (SBET).

For more information, see the GPS/IMU graphics in Attachment 3: GPS IMU Images. Software used included POSPac Software v. 8.7.

2.1.1. Trajectory Quality

The GNSS trajectory and high-quality IMU data are key factors in determining the overall positional accuracy of the final sensor data. Within the trajectory processing, there are many factors that affect the overall quality, but the most indicative are the combined separation, the estimated positional accuracy, and the Positional Dilution of Precision (PDOP).

2.1.2. Combination Separation

Combined separation is a measure of the difference between the forward-run and the backward-run solution of the trajectory. The Kalman filter was processed in both directions to remove the combined directional anomalies. In general, when these two solutions match closely, an optimally accurate and reliable solution is achieved. The data for this task order was processed with a goal to maintain a combined separation difference of less than 10-cm.

2.1.3. Estimated Positional Accuracy

Estimated positional accuracy plots the standard deviations of the east, north, and vertical directions along a time scale of the trajectory. It illustrates loss of satellite lock issues, as well as issues arising from long baselines, noise, and/or other atmospheric interference.

2.1.4. PDOP

The PDOP measures the precision of the GPS solution in regard to the geometry of the satellites acquired and used for the solution. Lidar data for this task order was processed with a goal to maintain an average PDOP value below 3.0. Brief periods of PDOP over 3.0 are acceptable due to the calibration and control process if other metrics are within specification.

2.2. Geometric Calibration

Each sensor is initially factory calibrated. Further adjustment is performed on each sensor by periodically flying boresight locations and using this data to update boresight values used in data processing. Various proprietary tools and methodologies are used during this process. Once all data has been processed with updated boresight values, FL to FL match is performed by using strip align and other proprietary tools/processes.

Point clouds were created using the RiPROCESS software. The generated point cloud is the mathematical three-dimensional composite of all returns from all laser pulses as determined from the aerial mission. The flight line strips are calibrated using Strip Align software. This process involves correcting for systematic errors remaining in the dataset after the boresight values are applied to the dataset. Corrections are made from line to line as well as from lift to lift in order improve the relative accuracy of the dataset and exceed specifications. Each adjusted flight line channel is merged using proprietary software to form the final flight line strips. The point cloud data is then imported into GeoCue, where they are then cut into a tiled dataset. Automated ground macros are run, and the vertical accuracy of the calibrated point cloud is tested against the surveyed ground control and any bias is validated, and the remaining bias is removed from the data using a TerraScan macro that is run through the GeoCue distributive process.

2.2.1. PDOP

The PDOP measures the precision of the GPS solution in regard to the geometry of the satellites acquired and used for the solution. Lidar data for this task order was processed with a goal to maintain an average PDOP value below 3.0. Brief periods of PDOP over 3.0 are acceptable due to the calibration and control process if other metrics are within specification.

2.3. Relative Accuracy: Horizontal

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% of the time. Based on a flying altitude of 910 meters, an IMU error of 0.003 decimal degrees, and a GNSS positional error of 0.018 meters, this project was compiled to meet 0.15 meter horizontal accuracy at the 95% confidence level. A summary is shown below.

Table 3.4.1 Horizontal Accuracy Results

Horizontal Accuracy	
RMSEr	0.087 ft
	0.29 m
ACCr	0.49 ft
	0.15 m

2.4. Relative Accuracy: Vertical

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 MN Central Mississippi River project was 0.038 feet (0.012 meters). A summary is shown below.

Table 3.5.1 Vertical Accuracy Results

Relative Vertical Accuracy	
Sample	186 flight line surfaces
Average	0.038 ft
	0.012 m
Median	0.037 ft
	0.011 m
RMSE	0.038 ft
	0.012 m
Standard Deviation	0.003 ft
	0.001 m
1.96σ	0.005 ft
	0.002 m

2.5. Lidar Data Classification

The classification classes are determined by Lidar Base Specifications 2021 Rev. A and are an industry standard for the classification of lidar point clouds. The calibrated data are automatically classified to the classification scheme using routines within the TerraScan software. After automated classification, the data are then manually reviewed using TerraScan and TerraModeler software packages to remove any remaining artifacts from the bare earth class (ASPRS Class 2). Bridge Breaklines are also added to reduce tinning in the surface during manual review. Final statistical analysis was performed per tile on the LAS files classes to verify final classification metrics and full LAS header information. Those classes include:

- Class 1: Processed, but Unclassified
- Class 2: Bare Earth
- Class 7: Low Noise
- Class 9: Water
- Class 17: Bridge Deck
- Class 18: High Noise
- Class 20: Ignored Ground
- Class 22: Temporal Exclusion

Classified LAS files were evaluated through a series of manual quality control steps as well as a peer-based review to eliminate remaining artifacts from the Ground class. This included a review of the DEM surface to remove artifacts and ensure topographic quality.

Software used included proprietary software, GeoCue and TerraScan.

High and low noise are classified in one of two ways. The first way is to identify and classify noise through a variety of different techniques and steps within TerraScan macros. This process happens during the initial grounding of the data and is fully automated. Macros are also used in targeted areas to correctly classify any noise that makes it through the automated steps without being classified correctly. The second method is to manually classify noise points as they are encountered during the manual ground surface review as well as the QA process. Any erroneous noise points identified either through automated routines or manual review were classified to the appropriate low or high noise class (ASPRS Class 7 and/or ASPRS Class 18) and flagged with the withheld bit.

2.6. Hydrologic Flattening

Using heads-up digitization, all Lake-Ponds, Double Line Drains, and Islands are manually collected that are within the project size specification. This includes Lake-Ponds greater than 2 acres in size, Double Line Drains with greater than a 100 foot nominal width, and Islands greater than 1 acre in size within a collected hydro feature. Lidar intensity imagery and bare-earth surface models are used to ensure appropriate and complete collection of these features.

Elevation values are assigned to all collected hydro features via using Geospatial's proprietary software. This software sets Lake-Ponds to an appropriate, single elevation to allow for the generation of hydro-flattened digital elevation models (DEM). Double Line Drain elevations are assigned based on lidar elevations and surrounding terrain feature to ensure all breaklines match the lidar within acceptable tolerances. Some deviation is expected between breakline and lidar elevations due to monotonicity, connectivity, and flattening rules that are enforced on the breaklines. Once completeness, horizontal placement, and vertical variances are reviewed, all breaklines are evaluated for topological consistency and data integrity using a combination of proprietary tools and manual review of hydro-flattened DEMs.

Breaklines are combined into one seamless shapefile, clipped to the project boundary, and imported into an Esri file geodatabase for delivery.

The calibrated data are automatically classified to the classification scheme using routines within the TerraScan software. After automated classification, the data are then manually reviewed using TerraScan and TerraModeler software packages to remove any remaining artifacts from the bare earth class (ASPRS Class 2). Bridge breaklines are also added to reduce tinning in the surface during the manual review.

Any erroneous noise points identified either through automated routines or manual review were classified to the appropriate low or high noise class (ASPRS Class 7 and/or ASPRS Class 18) and flagged with the withheld bit.

2.7. Digital Elevation Model

Hydro-Flattened DEMs (topographic) represent a lidar-derived product illustrating the grounded terrain and associated breaklines (as described above) in raster form. Proprietary software was used to take all input sources (bare earth lidar points, bridge and hydro breaklines, etc.) and create a Triangulated Irregular Network (TIN) on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper triangulation can occur. From the TIN, linear interpolation is used to calculate the cell values for the raster product. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF DEM was generated for each tile with a pixel size of 0.5-meter. Proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each DEM is reviewed in Global Mapper to check for any surface anomalies and to ensure a seamless dataset. Checks are run using propriety software to ensures there are no void or no-data values (-999999) in each derived DEM by checking all cell values that fall within the project boundary. A propriety tool is used to check all formatting requirements of the DEMs against what is required before final delivery.

2.8. Digital Elevation Model

Hydro-Flattened DEMs (topographic) represent a lidar-derived product illustrating the grounded terrain and associated breaklines (as described above) in raster form. Proprietary software was used to take all input sources (bare earth lidar points, bridge and hydro breaklines, etc.) and create a Triangulated Irregular Network (TIN) on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper triangulation can occur. From the TIN, linear interpolation is used to calculate the cell values for the raster product. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF DEM was generated for each tile with a pixel size of 0.5-meter. Proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each DEM is reviewed in Global Mapper to check for any surface anomalies and to ensure a seamless dataset. Checks are run using propriety software to ensures there are no void or no-data values (-999999) in each derived DEM by checking all cell values that fall within the project boundary. A proprietary tool is used to check all formatting requirements of the DEMs against what is required before final delivery.

2.9. Intensity Imagery

Intensity images represent reflectivity values collected by the lidar sensor during acquisition. Proprietary software generates intensity images using first returns and excluding those flagged with a withheld bit. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written during product generation.

2.10. Swath Separation Image

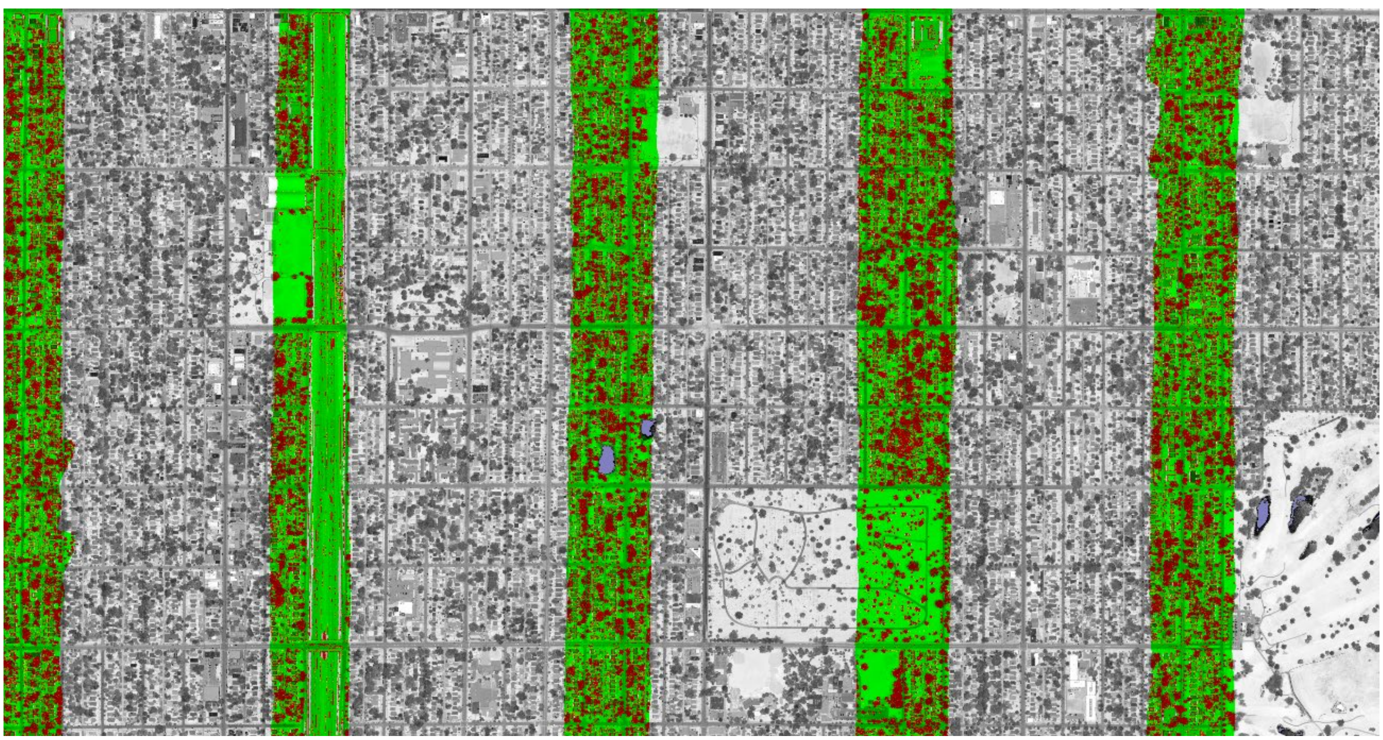
Swath Separation Images are rasters that represent the interswath alignment between flight lines and provide a qualitative evaluation of the positional quality of the point cloud. Proprietary software was used to generate 0.5-meter raster images in GeoTIFF format using last returns, excluding points flagged with the withheld bit, and using a point-in-cell algorithm. Images are generated with a 75% intensity opacity and (4) absolute 8-cm intervals, see below for interval coloring. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written to the file during product generation. A proprietary tool was uses to check all formatting requirements of the images against what is required before final delivery.

Software used was propriety internal software.

The color ramp for the swath separation image is as follows:

- Less than 8-cm: Green
- 8 to 16-cm: Yellow
- Greater than 16-cm: Red

Figure 3.10.1 Swath Separation Image



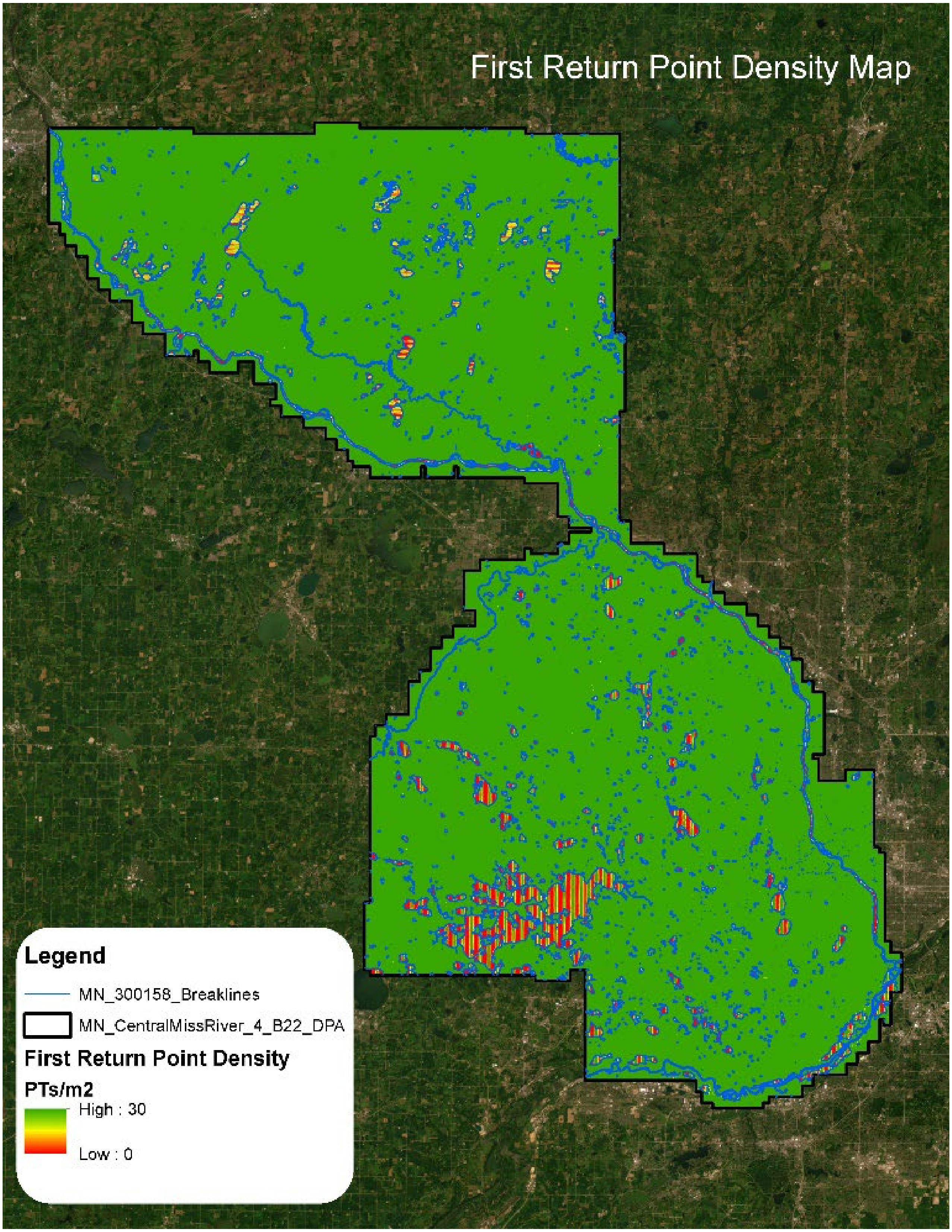
2.11. Lidar Density

The acquisition parameters were designed to acquire an average first-return density of 30 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 greater than 1 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 project was 48.1 (points/m*2*) while the average ground classified density was 34.9 (points/m*2*).

Figure 3.11.1 First Return Ground Point Density



2.12. Metadata

FGDC CSDGM/USGS MetaParser-compliant metadata was produced in XML format. The metadata includes a complete description of the task order client information, contractor information, project purpose, lidar acquisition and ground survey collection parameters, lidar acquisition and ground survey collection dates, spatial reference system information, data processing including acquisition quality assurance procedures, GPS and base station processing, geometric calibration, lidar classification, hydrologic flattening, intensity imagery development, and final product development.

Other metadata deliverables included:

- Data extent
- Tile index
- Swath separation images in GeoTIFF format
- Maximum Surface Height Rasters in GeoTIFF format