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# USGS CO NWCO 1 2020 & USGS CO NWCO 2 2020 (QL2)

**Project ID: 194684 Work Unit ID: 194681 & 227736**

# Lidar Mapping Report

February 2022

## EXECUTIVE SUMMARY


The Sanborn Map Company, Inc. (Sanborn) was tasked to provide remote sensing services in the form of lidar. Utilizing a multi-return system, Light Detection and Ranging (Lidar) detects 3-dimensional positions and attributes to form a point cloud. The high accuracy airborne system is integrated with both Global Navigation Satellite System (GNSS) and an Inertial Measure Unit (IMU) for accurate position and orientation. Acquisition of the project area's ~13,015mi² was completed on August 28th, 2021.

The Leica TerrainMapper was used to collect data for the aerial survey campaign. The sensor is attached to the aircraft's underside and emits rapid laser pulses that are used to calculate ranges between the aircraft and subsequent terrain below. The Airborne Lidar System (ALS) is boresighted by completing multiple passes over a known ground surface before the project acquisition. During data processing, the system calibration parameters are updated and used during post-processing of the lidar point cloud.

Differential GNSS unit in aircraft sampled positions at 2Hz or higher frequency. Lidar data was only acquired when GNSS PDOP is ≤4 and at least 6 satellites are in view. Collection conditions were for leaf-off vegetation. The atmosphere was free of clouds and fog between the aircraft and ground. The ground was free of snow and extensive flooding or any other type of inundation.

The contents of this report summarize the methods used to establish the base station coordinates, perform the lidar data acquisition and processing as well as the results of these methods.

# CONTENTS

# 1.0 INTRODUCTION

This document contains the technical write-up of the lidar campaign, including system calibration techniques, and the collection and processing of the lidar data.

## 1.1 Contact Information

Questions regarding the technical aspects of this report should be addressed to:


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## 1.2 Purpose of Lidar Acquisition

The objective of this project is to collect accurate measurements of the bare-earth surface as well as above ground features to be provided as geometric inputs for surface and/or change modeling as is relates survey assessments.

## 1.3 Project Location

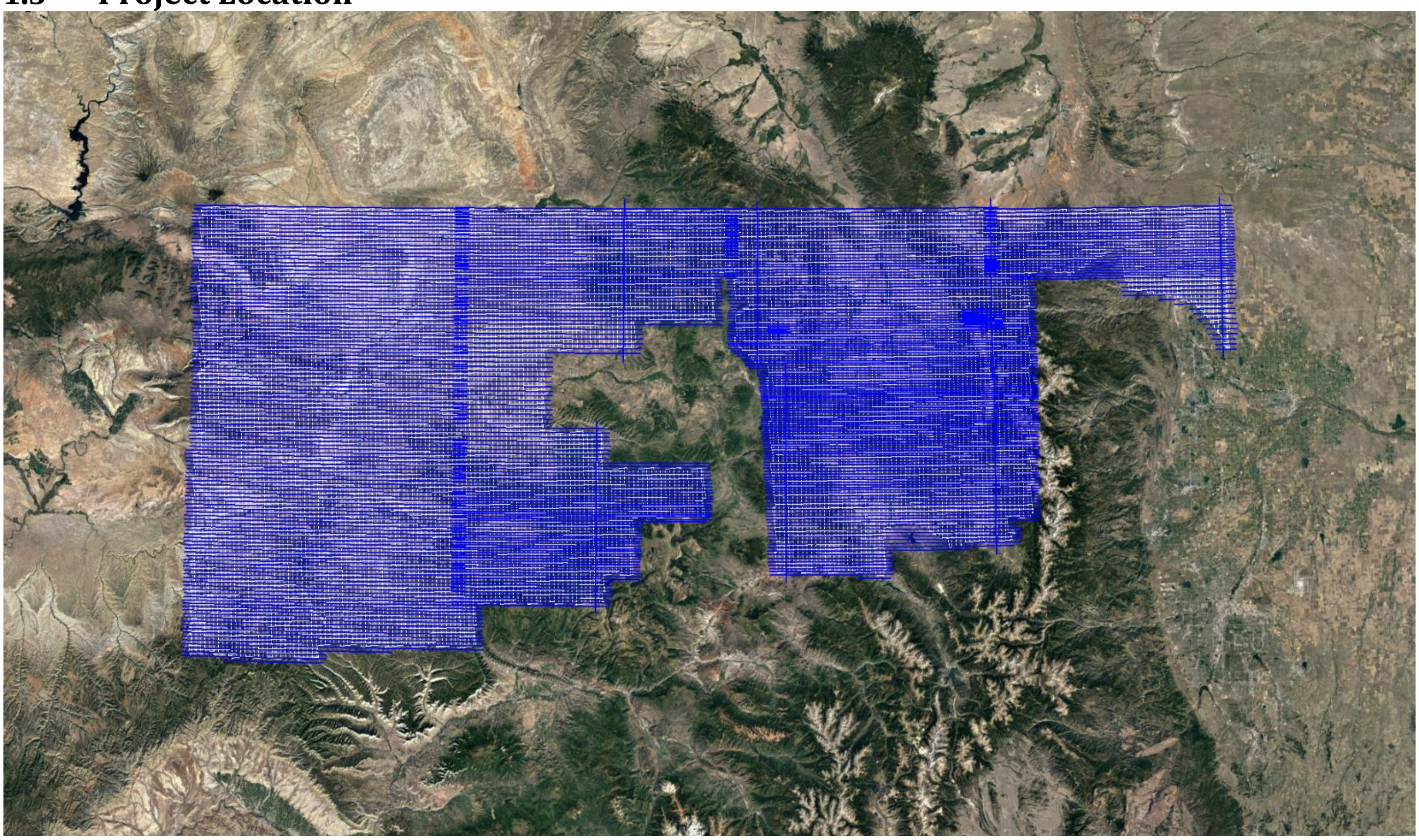


Figure 1: Tile Index and Trajectories As-Flown

# 2.0 ACQUISITION

## 2.1 Introduction

This section outlines the lidar system, flight reporting, and data acquisition methodology used during the collection of the lidar campaign. Although Sanborn conducts all lidar missions with the same rigorous and strict procedures and processes, all lidar collections are unique.

## 2.2 Acquisition Parameters

Sanborn specifically defined the collection parameters to accomplish the desired project specifications. **Table 1** shows the planned acquisition parameters utilized for this aerial survey with the sensor(s) installed.

| Planned Acquisition Parameters | | | |
|---|---|---|---|
| **Aircraft** | N278RC - PIPER PA-31-310 | N500Q - PIPER PA-31-310 | N735BT - CESSNA TU206G |
| **Sensor** | Leica TerrainMapper | Leica TerrainMapper | Leica TerrainMapper |
| **Max Number of Returns** | 15 | 15 | 15 |
| **Point Spacing (m)** | 0.66 | 0.66 | 0.66 |
| **Point Density (pls/m²)** | 2.1 | 2.1 | 2.1 |
| **Flying Height (AGL) (m)** | 3050 | 3050 | 3050 |
| **Air Speed (kts)** | 160 | 160 | 160 |
| **Field of View (degrees)** | 40 | 40 | 40 |
| **Scan Rate (Hz)** | 88.4 | 88.4 | 88.4 |
| **Pulse Rate (kHz)** | 667.1 | 667.1 | 667.1 |
| **Laser Footprint (m)** | 0.71 | 0.71 | 0.71 |
| **Wavelength (nm)** | 1064 | 1064 | 1064 |
| **Multi-Pulse** | Yes | Yes | Yes |
| **Swath Width (m)** | 2220 | 2220 | 2220 |
| **Overlap (%)** | 20 | 20 | 20 |

Table 1: Lidar Acquisition Parameters

## 2.3 Field Work Procedures

Sanborn's standard procedure before every mission is to perform pre-flight checks to ensure correct operation of all systems. All cables were checked, and the sensor head glass was cleaned. A three-minute static session was conducted on the ground with the engines running prior to take-off to establish fine-alignment of the IMU and to resolve GNSS ambiguities.

The project acquisition consisted of sixty-one (61) mission(s). During the data collection, the operator recorded information on log sheets which includes weather conditions, lidar operation parameters, flight line statistics and PDOP.

Preliminary data processing was performed in the field immediately following the missions for quality control of GNSS data and to ensure sufficient coverage of the project AOI. Any problematic data could then be re-flown immediately as required. Final data processing was completed in the Colorado Springs, CO office. **Table 2** below shows the flight acquisition metrics for the entire collection.

| Date | Sensor | Serial # | Tail # | MissionID | PDOP | Start (UTC) | End (UTC) |
|---|---|---|---|---|---|---|---|
| 6/20/2020 | TerrainMapper | TM91555 | N500Q | 20200620A | 1.1 | 17:52:01 | 21:24:58 |
| 6/21/2020 | TerrainMapper | TM91555 | N500Q | 20200621A | 1.2 | 15:09:18 | 15:49:48 |
| 6/22/2020 | TerrainMapper | TM91555 | N500Q | 20200622A | 1.1 | 13:38:07 | 15:07:43 |
| 6/23/2020 | TerrainMapper | TM91555 | N500Q | 20200623A | 1.1 | 13:37:34 | 15:19:50 |
| 6/24/2020 | TerrainMapper | TM91555 | N500Q | 20200624A | 1.0 | 12:37:13 | 16:09:52 |
| 7/17/2020 | TerrainMapper | TM91555 | N735BT | 20200717A | 1.0 | 14:53:28 | 17:48:08 |
| 7/18/2020 | TerrainMapper | TM91555 | N735BT | 20200718A | 1.1 | 17:08:20 | 19:18:50 |
| 7/19/2020 | TerrainMapper | TM91555 | N735BT | 20200719A | 1.1 | 13:05:29 | 17:48:11 |
| 7/20/2020 | TerrainMapper | TM91555 | N735BT | 20200720A | 1.0 | 13:01:38 | 18:13:54 |
| 7/20/2020 | TerrainMapper | TM91555 | N735BT | 20200720B | 1.1 | 19:25:08 | 21:32:41 |
| 7/21/2020 | TerrainMapper | TM91555 | N735BT | 20200721A | 1.1 | 12:54:29 | 17:19:18 |
| 7/21/2020 | TerrainMapper | TM91555 | N735BT | 20200721B | 1.1 | 18:51:50 | 20:55:54 |
| 7/23/2020 | TerrainMapper | TM91555 | N735BT | 20200723A | 1.0 | 13:15:41 | 14:47:12 |
| 7/26/2020 | TerrainMapper | TM91555 | N735BT | 20200726A | 1.1 | 13:02:46 | 16:39:03 |
| 7/27/2020 | TerrainMapper | TM91555 | N735BT | 20200727A | 1.1 | 12:55:15 | 15:20:03 |
| 7/29/2020 | TerrainMapper | TM91555 | N735BT | 20200729A | 1.0 | 13:47:39 | 16:22:35 |
| 7/30/2020 | TerrainMapper | TM91520 | N500Q | 20200730A | 1.0 | 16:39:00 | 17:25:43 |
| 7/31/2020 | TerrainMapper | TM91520 | N500Q | 20200731A | 1.1 | 13:02:01 | 17:14:12 |
| 8/1/2020 | TerrainMapper | TM91555 | N735BT | 20200801A | 1.0 | 13:03:35 | 13:37:48 |
| 8/2/2020 | TerrainMapper | TM91520 | N500Q | 20200802A | 1.1 | 13:46:26 | 16:16:16 |
| 8/3/2020 | TerrainMapper | TM91520 | N500Q | 20200803A | 1.0 | 13:52:25 | 16:25:16 |
| 8/6/2020 | TerrainMapper | TM91520 | N500Q | 20200806A | 1.1 | 17:19:42 | 18:05:44 |
| 8/7/2020 | TerrainMapper | TM91520 | N500Q | 20200807A | 1.1 | 13:53:10 | 16:41:15 |
| 8/8/2020 | TerrainMapper | TM91520 | N500Q | 20200808A | 1.1 | 13:56:00 | 16:19:16 |
| 8/9/2020 | TerrainMapper | TM91520 | N500Q | 20200809A | 1.1 | 14:13:36 | 16:35:45 |
| 8/10/2020 | TerrainMapper | TM91520 | N500Q | 20200810A | 1.1 | 13:40:24 | 16:52:51 |
| 8/11/2020 | TerrainMapper | TM91520 | N500Q | 20200811A | 1.1 | 12:37:56 | 15:56:55 |
| 8/11/2020 | TerrainMapper | TM91520 | N500Q | 20200811B | 1.1 | 17:18:37 | 19:17:47 |
| 8/12/2020 | TerrainMapper | TM91520 | N500Q | 20200812A | 1.1 | 12:56:54 | 15:22:38 |
| 8/13/2020 | TerrainMapper | TM91520 | N500Q | 20200813A | 1.2 | 12:42:51 | 16:09:33 |
| 8/14/2020 | TerrainMapper | TM91520 | N500Q | 20200814A | 1.1 | 13:27:59 | 16:43:09 |
| 8/14/2020 | TerrainMapper | TM91520 | N500Q | 20200814B | 1.2 | 16:04:54 | 16:05:43 |
| 8/14/2020 | TerrainMapper | TM91555 | N735BT | 20200814A | 1.2 | 14:28:46 | 15:15:14 |
| 8/15/2020 | TerrainMapper | TM91520 | N500Q | 20200815A | 1.3 | 15:19:09 | 16:36:09 |
| 8/15/2020 | TerrainMapper | TM91555 | N735BT | 20200815A | 1.1 | 13:31:53 | 14:58:55 |
| 8/16/2020 | TerrainMapper | TM91520 | N500Q | 20200816A | 1.2 | 12:56:59 | 16:48:06 |
| 8/17/2020 | TerrainMapper | TM91520 | N500Q | 20200817A | 1.1 | 12:50:57 | 16:03:50 |
| 8/18/2020 | TerrainMapper | TM91520 | N500Q | 20200818A | 1.1 | 12:54:21 | 16:32:58 |
| 8/19/2020 | TerrainMapper | TM91520 | N500Q | 20200819A | 1.1 | 12:54:28 | 15:30:41 |
| 8/20/2020 | TerrainMapper | TM91555 | N735BT | 20200820A | 1 | 14:07:15 | 17:19:26 |
| 8/31/2020 | TerrainMapper | TM91555 | N735BT | 20200831A | 1.1 | 15:45:05 | 17:38:56 |
| 9/1/2020 | TerrainMapper | TM91520 | N278RC | 20200901A | 1.1 | 20:25:47 | 0:09:19 |
| 9/1/2020 | TerrainMapper | TM91555 | N735BT | 20200901B | 1 | 20:56:31 | 22:31:45 |
| 9/1/2020 | TerrainMapper | TM91555 | N735BT | 20200901C | 1 | 22:52:25 | 0:24:25 |
| 9/2/2020 | TerrainMapper | TM91520 | N278RC | 20200902A | 1.1 | 15:04:04 | 19:28:44 |
| 9/3/2020 | TerrainMapper | TM91520 | N278RC | 20200903A | 1 | 15:50:39 | 20:45:55 |
| 9/3/2020 | TerrainMapper | TM91555 | N735BT | 20200903B | 1.1 | 20:40:58 | 23:10:40 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 9/4/2020 | TerrainMapper | TM91555 | N735BT | 20200904A | 1 | 15:03:25 | 19:35:40 |
| 9/4/2020 | TerrainMapper | TM91555 | N735BT | 20200904B | 1.1 | 17:05:24 | 17:49:56 |
| 9/4/2020 | TerrainMapper | TM91520 | N278RC | 20200904C | 1.1 | 19:34:23 | 20:20:58 |
| 9/5/2020 | TerrainMapper | TM91555 | N735BT | 20200905A | 1.1 | 14:35:47 | 18:41:32 |
| 9/5/2020 | TerrainMapper | TM91520 | N278RC | 20200905B | 1.1 | 15:17:42 | 20:14:15 |
| 9/6/2020 | TerrainMapper | TM91555 | N735BT | 20200906A | 1.1 | 14:29:24 | 17:44:02 |
| 9/6/2020 | TerrainMapper | TM91520 | N278RC | 20200906B | 1.1 | 17:06:20 | 18:43:44 |
| 10/1/2020 | TerrainMapper | TM91555 | N500Q | 20201001A | 1.1 | 18:12:04 | 19:21:02 |
| 10/3/2020 | TerrainMapper | TM91555 | N500Q | 20201003A | 1.2 | 14:56:16 | 18:02:30 |
| 10/3/2020 | TerrainMapper | TM91555 | N500Q | 20201003B | 1.1 | 21:06:28 | 21:41:08 |
| 10/4/2020 | TerrainMapper | TM91555 | N500Q | 20201004A | 1.2 | 15:13:44 | 17:02:01 |
| 10/7/2020 | TerrainMapper | TM91555 | N500Q | 20201007A | 1.2 | 17:57:03 | 18:17:35 |
| 8/24/2021 | TerrainMapper | TM91555 | N500Q | 20210824B | 1.3 | 17:39:11 | 17:44:41 |
| 8/28/2021 | TerrainMapper | TM91555 | N500Q | 20210828A | 1.1 | 15:10:48 | 15:45:33 |

Table 2: Collection Date Time by Mission

# 3.0 PROCESSING

## 3.1 Introduction

The GNSS/IMU data was post-processed using Waypoint Inertial Explorer software to create Smoothed Best Estimate Trajectory (SBET) file(s). The SBET was then combined with the laser range measurements in Leica HxMap software to produce the 3-dimensional coordinates resulting in an accurate set of Raw Point Cloud (RPC) mass points. These raw swath (*.las) files are output in WGS84, UTM, Ellipsoid, Meters and transformed to the project Coordinate Reference System (CRS) upon ingest into GeoCue before project wide lidar matching.

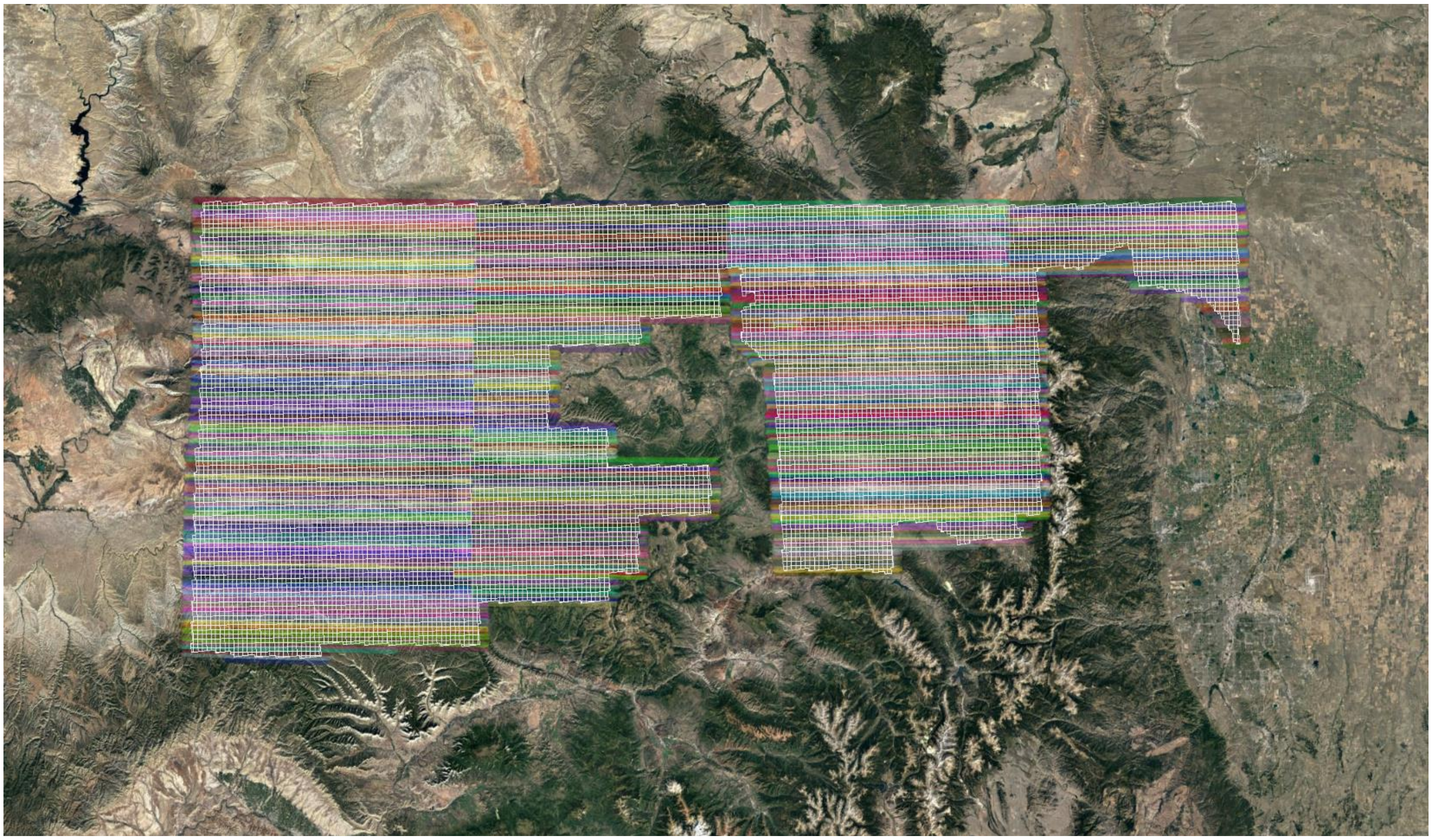


Figure 2: Raw Swath Coverage

The Leica HxMap pre-processing software created raw swath files with all return values. This multi-return information was processed and classified to obtain the required feature for delivery. All lidar data is processed using the ASPRS binary LAS format version 1.4. **Table 3** illustrates the achieved point cloud statistics.

| Category | Value |
|---:|---|
| Aggregate Total Points | 224,773,971,554 |
| Aggregate Nominal Pulse Spacing (m) | 0.44 |
| Aggregate Nominal Pulse Density (pls/m²) | 5.3 |
| Aggregate Nominal Pulse Spacing (ft) | 1.43 |
| Aggregate Nominal Pulse Density (pls/ft²) | 0.5 |

Table 3: Point Cloud Statistics

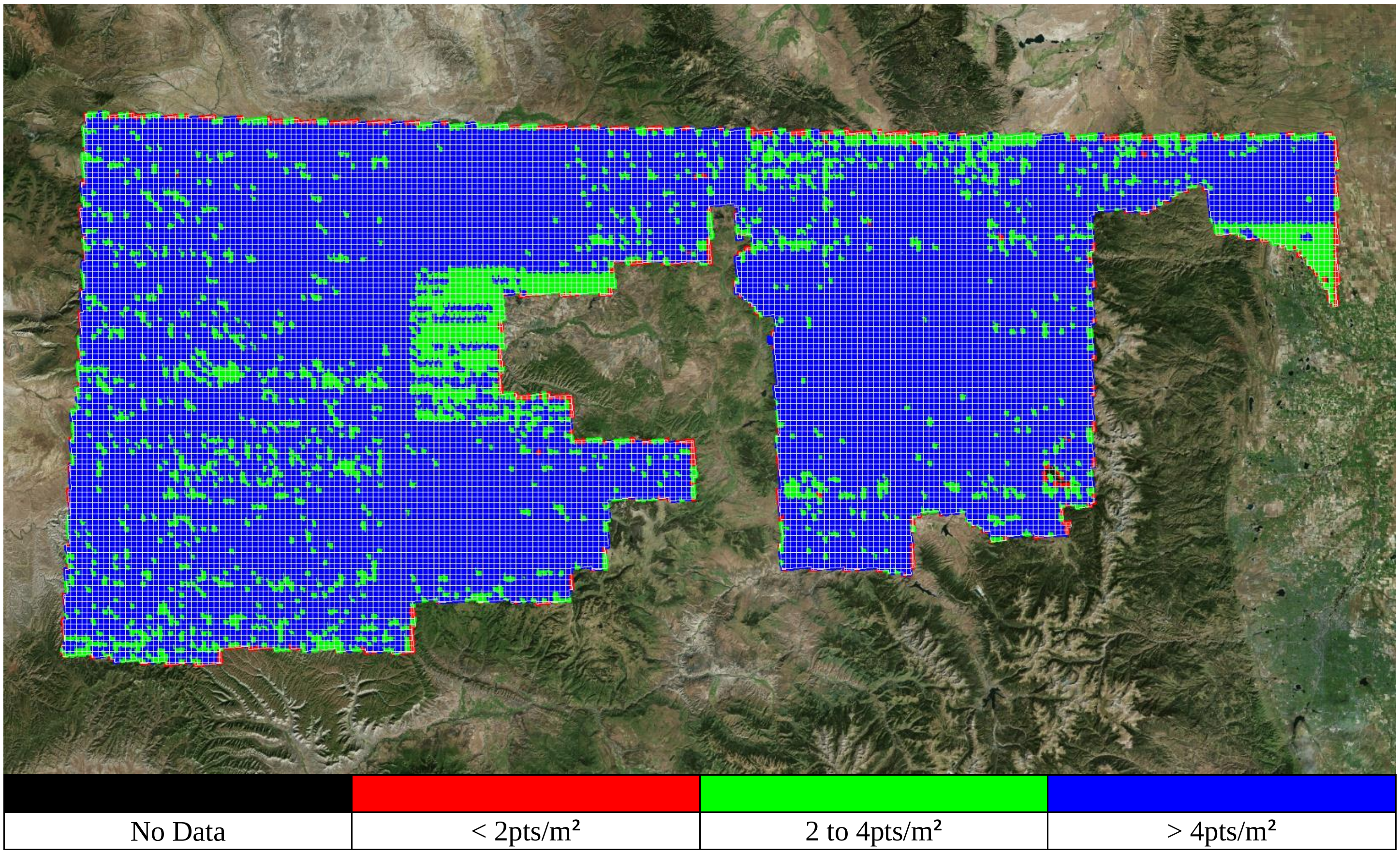



Figure 3: Point Cloud Density

## 3.2 Coordinate Reference System

**Horizontal Datum:** North American Datum of 1983 (2011)
**Projection:** State Plane Colorado North (FIPS 0501)
**Vertical Datum:** North American Vertical Datum of 1988
**Geoid Model:** Geoid18
**Units:** U.S. Survey Feet

### 3.3 Lidar Matching

Sanborn uses pre-processing software and the latest boresight values to combine the processed SBET with the laser scan files to produce the lidar point cloud. The data is processed by mission and/or block and is output in ASPRS LASv1.4 Point Data Record Format (PDRF) 6 with 16bit linearly scaled intensities to the nearest 0.001 3D position. Each mission is produced in WGS84, UTM, Ellipsoid, Meters and transformed to the project CRS upon import into GeoCue.

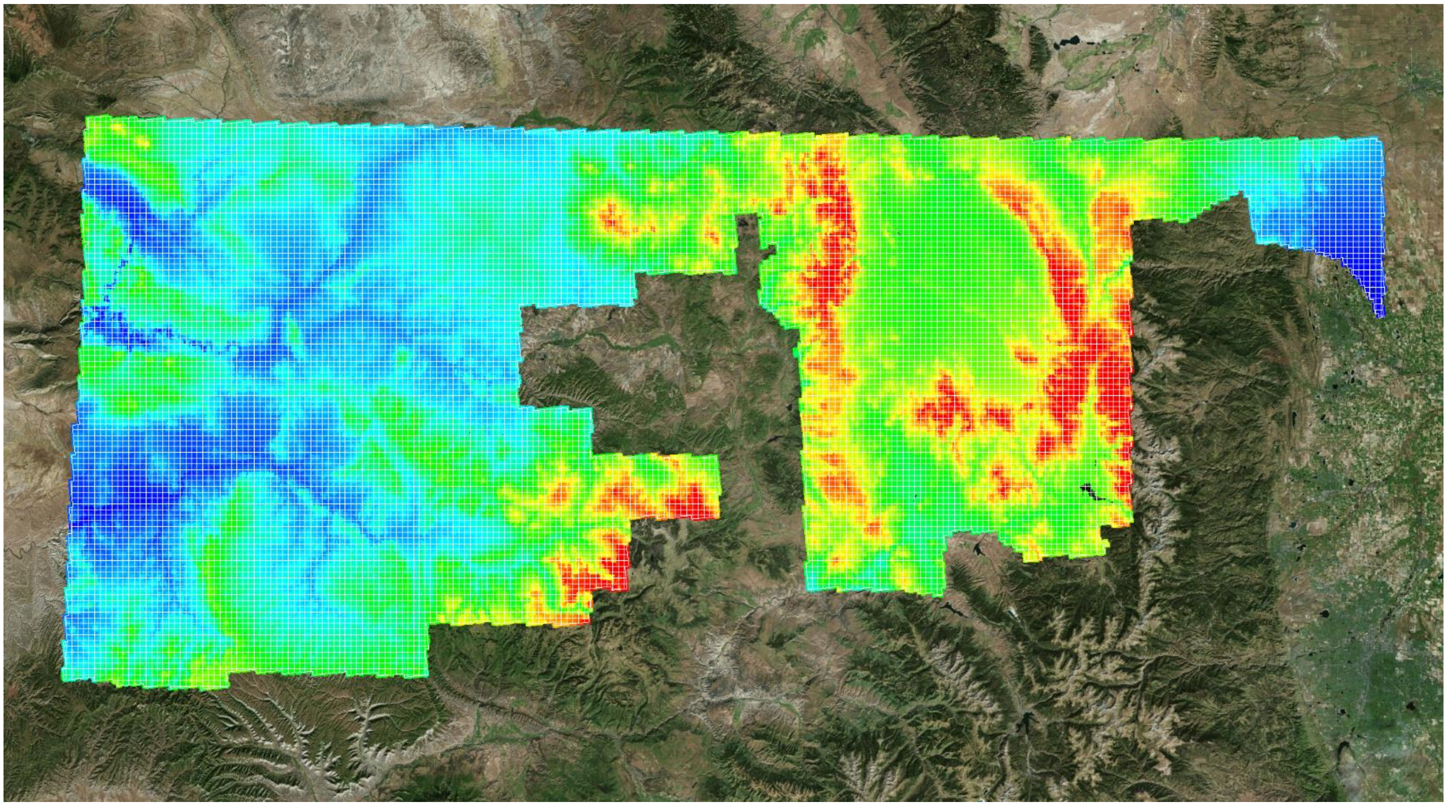


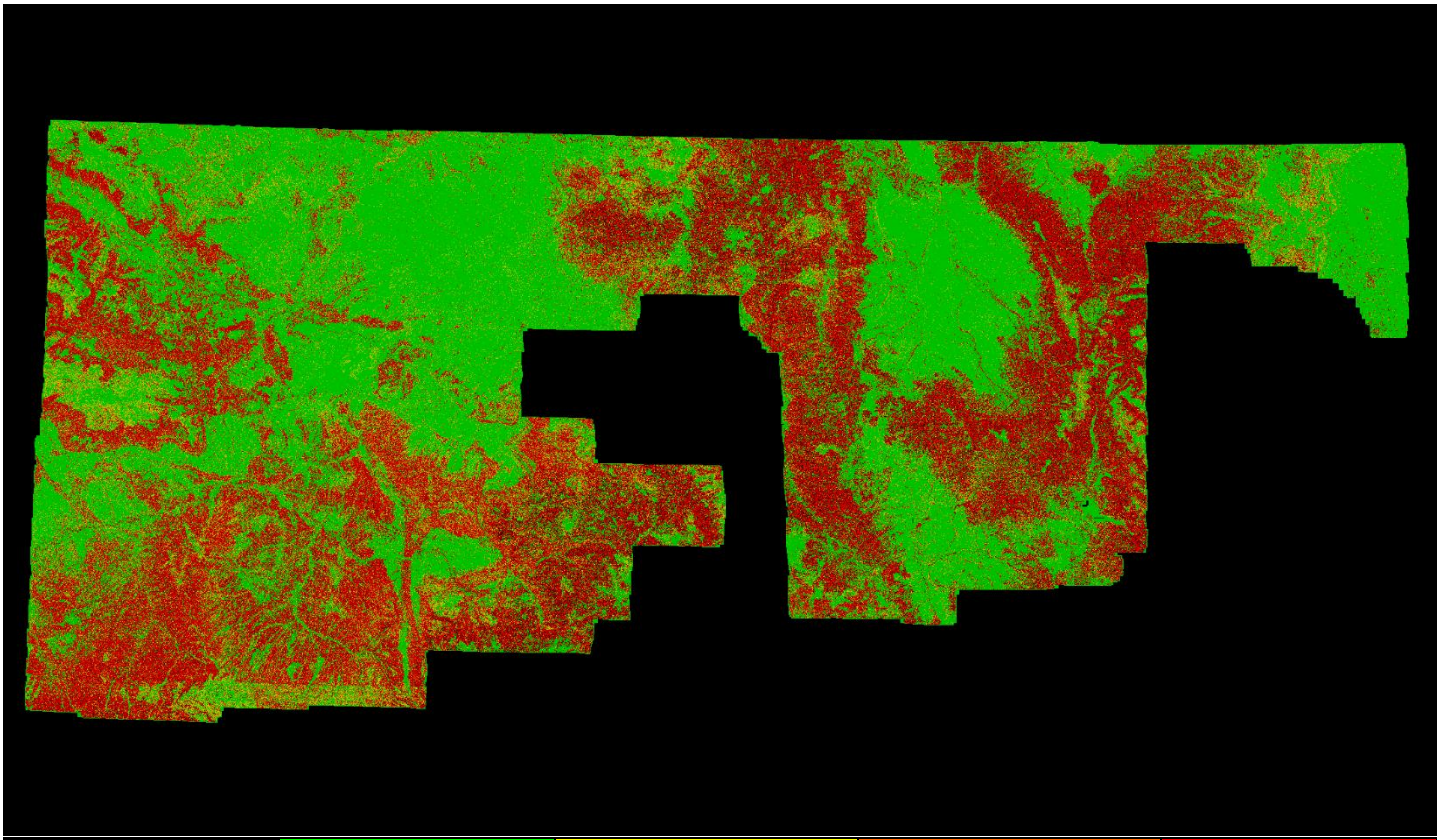
Figure 4: Point Cloud Elevation

Each mission is imported into GeoCue where each individual flight line is assigned a unique Source ID number. The SBET is cut per swath into TerraScan Trajectory files based on Source ID number and timestamp; these are utilized during the lidar matching process. The project area(s) are broken into logical blocks based on AOIs or predetermined delivery blocks and the individual flight lines are populated into lidar matching tile grids. These lidar matching tile grids are prepared for scanner, line, mission, block and eventual project wide lidar matching routines by first running point cloud filters to identify ground and building features to be used during any TerraMatch processes.

Sanborn takes advantage of both visual and statistical validation methodologies to review and ensure both the individual precision and alignment of the lidar dataset. Swath Precision Images modulated by Intensity are representative of the intraswath alignment and provide a holistic qualitative look at the goodness of fit within each swath. Swath Separation Images modulated by Intensity are representative of the interswath alignment and provide a holistic qualitative look at the positional quality of the point cloud. The images are reviewed in their entirety. Furthermore, the set of TerraMatch Tie Lines are used to produce a Tie Line Report to statistically assess the X. Y. and Z offset averages and magnitudes for the whole project including each line individually. This visual and statistical review guarantees the relative accuracy of the lidar dataset. **Table 4** outlines the relative accuracy requirements of the project. **Tables 5 – 8** are the relative accuracies achieved.

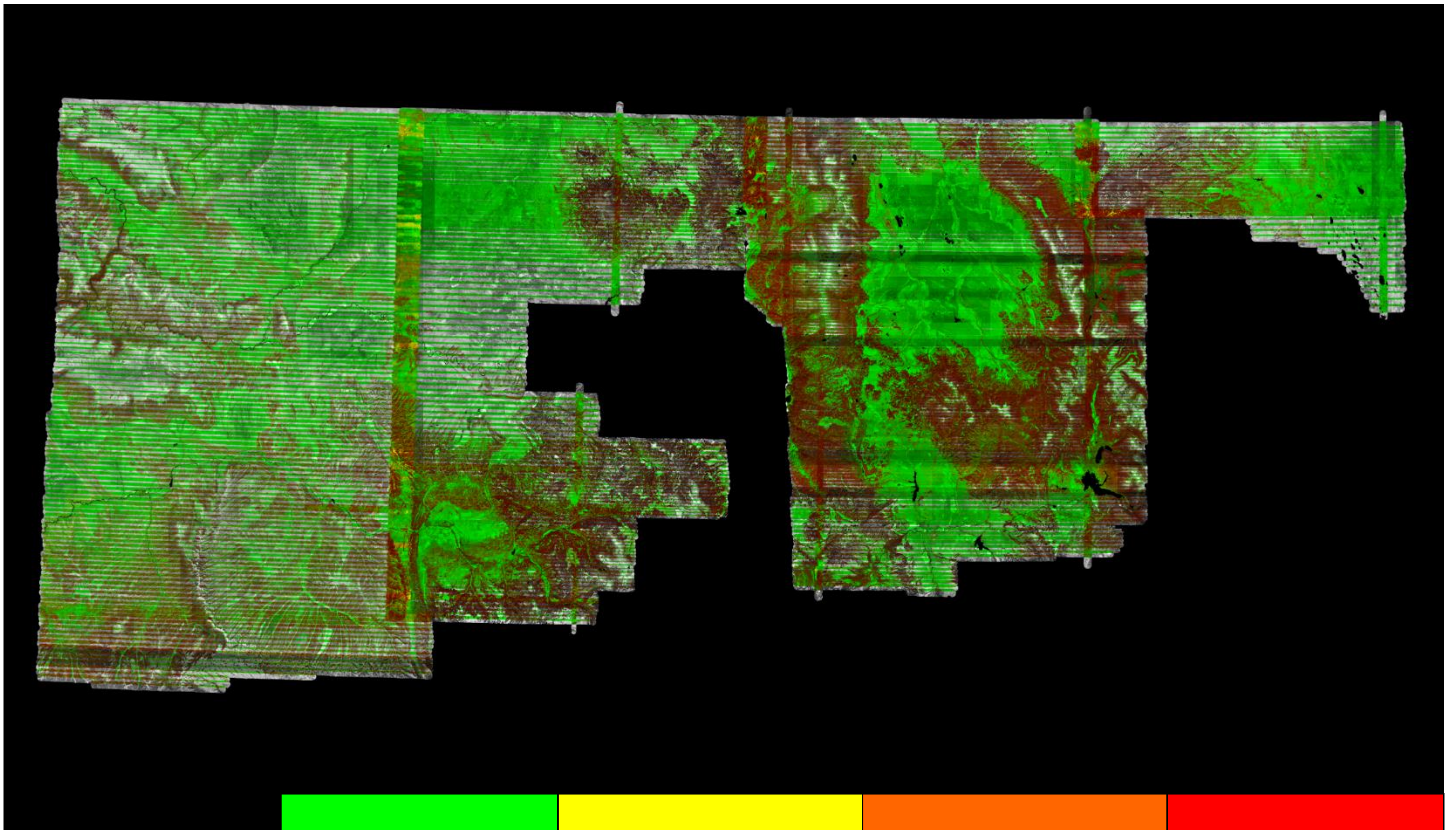
| Category | Value (m) | Value (ft) |
|---|---|---|
| Smooth Surface Repeatability | ≤0.060 | ≤0.197 |
| Swath overlap difference, RMSDz | ≤0.080 | ≤0.262 |

Table 4: Relative Accuracy Requirements



| | | | | |
|---|---|---|---|---|
| No Data | < 0.06m | 0.06m to 0.12m | 0.12m to 0.18m | > 0.18m |
| No Data | < 0.197ft | 0.197ft to 0.394ft | 0.394ft to 0.591ft | > 0.591ft |

Figure 5: Swath Precision



| No Data | < 0.08m | 0.08m to 0.16m | 0.16m to 0.24m | > 0.24m |
|---|---|---|---|---|
| No Data | < 0.262ft | 0.262ft to 0.524ft | 0.524ft to 0.786ft | > 0.786ft |

Figure 6: Swath Separation

| Line | X | Y | Z | Line | X | Y | Z | Line | X | Y | Z |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | - | - | 0.020 | **279** | 0.086 | 0.098 | 0.027 | **432** | 0.096 | 0.065 | 0.027 |
| **2** | - | - | 0.020 | **280** | 0.080 | 0.086 | 0.031 | **433** | 0.110 | 0.126 | 0.030 |
| **3** | 0.038 | 0.078 | 0.022 | **281** | 0.077 | 0.111 | 0.024 | **434** | 0.043 | 0.209 | 0.027 |
| **4** | 0.057 | 0.067 | 0.020 | **282** | 0.088 | 0.114 | 0.024 | **435** | 0.044 | 0.181 | 0.029 |
| **5** | 0.094 | 0.089 | 0.020 | **283** | 0.077 | 0.135 | 0.026 | **436** | 0.029 | 0.066 | 0.026 |
| **6** | 0.108 | 0.078 | 0.020 | **284** | 0.052 | 0.083 | 0.026 | **437** | 0.028 | 0.044 | 0.030 |
| **7** | 0.203 | 0.004 | 0.020 | **285** | 0.042 | 0.047 | 0.025 | **438** | 0.046 | 0.067 | 0.028 |
| **8** | 0.039 | 0.079 | 0.021 | **286** | 0.057 | 0.044 | 0.025 | **439** | 0.064 | 0.104 | 0.030 |
| **9** | - | - | 0.020 | **287** | 0.075 | 0.044 | 0.026 | **440** | 0.060 | 0.121 | 0.026 |
| **10** | 0.107 | 0.131 | 0.020 | **288** | 0.053 | 0.058 | 0.027 | **441** | 0.044 | 0.047 | 0.035 |
| **11** | 0.106 | 0.117 | 0.021 | **289** | 0.046 | 0.068 | 0.027 | **442** | 0.067 | 0.098 | 0.024 |
| **12** | 0.189 | 0.017 | 0.020 | **290** | 0.042 | 0.074 | 0.027 | **443** | 0.078 | 0.024 | 0.024 |
| **13** | 0.369 | 0.048 | 0.022 | **291** | 0.102 | 0.107 | 0.030 | **444** | 0.092 | 0.018 | 0.024 |
| **14** | - | - | 0.021 | **292** | 0.085 | 0.087 | 0.032 | **445** | 0.110 | 0.071 | 0.026 |
| **15** | 0.085 | 0.065 | 0.020 | **293** | 0.090 | 0.098 | 0.039 | **446** | 0.054 | 0.085 | 0.024 |
| **16** | 0.063 | 0.067 | 0.021 | **294** | 0.086 | 0.097 | 0.033 | **447** | 0.054 | 0.089 | 0.026 |
| **17** | 0.052 | 0.071 | 0.021 | **295** | 0.086 | 0.098 | 0.032 | **448** | 0.076 | 0.081 | 0.027 |
| **18** | 0.045 | 0.084 | 0.021 | **296** | 0.087 | 0.085 | 0.033 | **449** | 0.069 | 0.076 | 0.025 |
| **19** | 0.037 | 0.094 | 0.020 | **297** | 0.098 | 0.113 | 0.030 | **450** | 0.065 | 0.081 | 0.026 |
| **20** | - | - | 0.022 | **298** | 0.091 | 0.102 | 0.031 | **451** | 0.055 | 0.068 | 0.024 |
| **21** | 0.026 | 0.043 | 0.021 | **311** | 0.036 | 0.047 | 0.027 | **452** | 0.041 | 0.053 | 0.025 |
| **22** | 0.056 | 0.065 | 0.021 | **312** | 0.080 | 0.022 | 0.024 | **453** | 0.035 | 0.088 | 0.024 |
| **23** | 0.087 | 0.087 | 0.021 | **313** | 0.061 | 0.102 | 0.026 | **454** | 0.023 | 0.118 | 0.026 |
| **24** | - | - | 0.021 | **314** | 0.036 | 0.110 | 0.025 | **455** | 0.030 | 0.111 | 0.026 |
| **25** | - | - | 0.023 | **315** | 0.045 | 0.058 | 0.026 | **456** | 0.046 | 0.169 | 0.028 |
| **26** | 0.073 | 0.019 | 0.021 | **316** | 0.052 | 0.054 | 0.023 | **457** | 0.102 | 0.096 | 0.027 |
| **27** | 0.063 | 0.067 | 0.022 | **317** | 0.065 | 0.079 | 0.023 | **458** | 0.132 | 0.024 | 0.029 |
| **28** | 0.030 | 0.127 | 0.021 | **318** | 0.052 | 0.084 | 0.023 | **459** | - | - | 0.025 |
| **29** | - | - | 0.022 | **319** | 0.043 | 0.079 | 0.024 | **460** | 0.000 | 0.000 | 0.026 |
| **30** | 0.056 | 0.028 | 0.021 | **320** | 0.051 | 0.059 | 0.024 | **461** | 0.005 | 0.010 | 0.026 |
| **31** | 0.058 | 0.067 | 0.020 | **321** | 0.044 | 0.066 | 0.026 | **462** | 0.085 | 0.069 | 0.027 |
| **32** | 0.031 | 0.058 | 0.022 | **322** | 0.063 | 0.070 | 0.023 | **463** | - | - | 0.025 |
| **33** | 0.014 | 0.060 | 0.021 | **323** | 0.067 | 0.068 | 0.026 | **464** | 0.063 | 0.095 | 0.027 |
| **34** | 0.008 | 0.047 | 0.022 | **324** | 0.081 | 0.063 | 0.027 | **465** | 0.074 | 0.094 | 0.027 |
| **35** | 0.011 | 0.078 | 0.021 | **325** | 0.090 | 0.061 | 0.023 | **466** | 0.103 | 0.091 | 0.027 |
| **36** | - | - | 0.022 | **326** | 0.059 | 0.065 | 0.024 | **467** | 0.166 | 0.015 | 0.029 |
| **37** | 0.086 | 0.044 | 0.021 | **327** | 0.058 | 0.063 | 0.023 | **468** | 0.057 | 0.014 | 0.029 |
| **38** | 0.064 | 0.032 | 0.022 | **328** | 0.064 | 0.063 | 0.024 | **469** | 0.072 | 0.110 | 0.030 |
| **39** | 0.049 | 0.086 | 0.022 | **329** | 0.043 | 0.070 | 0.026 | **470** | 0.136 | 0.144 | 0.031 |
| **40** | 0.058 | 0.094 | 0.024 | **330** | 0.039 | 0.077 | 0.023 | **471** | 0.108 | 0.131 | 0.029 |
| **41** | 0.059 | 0.105 | 0.024 | **331** | 0.049 | 0.077 | 0.023 | **472** | 0.057 | 0.095 | 0.031 |
| **42** | 0.031 | 0.159 | 0.024 | **332** | 0.058 | 0.069 | 0.025 | **473** | 0.062 | 0.061 | 0.031 |
| **43** | 0.047 | 0.120 | 0.021 | **333** | 0.052 | 0.059 | 0.021 | **474** | 0.074 | 0.058 | 0.033 |
| **44** | 0.068 | 0.087 | 0.023 | **334** | 0.063 | 0.077 | 0.023 | **475** | 0.057 | 0.064 | 0.034 |
| **45** | 0.025 | 0.044 | 0.020 | **335** | 0.070 | 0.085 | 0.033 | **476** | 0.052 | 0.085 | 0.032 |
| **46** | 0.024 | 0.043 | 0.022 | **336** | 0.084 | 0.099 | 0.036 | **477** | 0.115 | 0.049 | 0.031 |
| **47** | 0.028 | 0.001 | 0.022 | **337** | 0.069 | 0.082 | 0.031 | **478** | 0.091 | 0.042 | 0.030 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **48** | 0.091 | 0.072 | 0.025 | **338** | 0.080 | 0.093 | 0.033 | **480** | 0.094 | 0.044 | 0.031 |
| **49** | 0.071 | 0.106 | 0.023 | **339** | 0.077 | 0.084 | 0.026 | **481** | 0.097 | 0.041 | 0.031 |
| **50** | 0.060 | 0.115 | 0.023 | **340** | 0.052 | 0.050 | 0.026 | **482** | 0.056 | 0.034 | 0.033 |
| **51** | 0.069 | 0.008 | 0.024 | **341** | 0.059 | 0.060 | 0.025 | **483** | 0.065 | 0.050 | 0.032 |
| **52** | 0.040 | 0.032 | 0.021 | **342** | 0.066 | 0.094 | 0.026 | **484** | 0.084 | 0.057 | 0.032 |
| **53** | 0.112 | 0.027 | 0.023 | **343** | 0.064 | 0.092 | 0.026 | **485** | 0.077 | 0.067 | 0.033 |
| **54** | 0.145 | 0.040 | 0.021 | **344** | 0.057 | 0.064 | 0.026 | **486** | 0.089 | 0.074 | 0.032 |
| **55** | 0.027 | 0.024 | 0.024 | **345** | 0.054 | 0.076 | 0.025 | **487** | 0.109 | 0.087 | 0.032 |
| **56** | 0.011 | 0.039 | 0.022 | **346** | 0.057 | 0.077 | 0.025 | **488** | 0.080 | 0.054 | 0.030 |
| **57** | 0.011 | 0.037 | 0.024 | **347** | 0.053 | 0.066 | 0.025 | **489** | 0.098 | 0.082 | 0.030 |
| **58** | 0.065 | 0.070 | 0.024 | **348** | 0.069 | 0.070 | 0.029 | **490** | 0.074 | 0.063 | 0.030 |
| **59** | 0.127 | 0.107 | 0.024 | **349** | 0.068 | 0.071 | 0.030 | **491** | 0.066 | 0.084 | 0.031 |
| **60** | 0.115 | 0.055 | 0.024 | **350** | 0.054 | 0.075 | 0.029 | **492** | 0.072 | 0.062 | 0.030 |
| **61** | 0.042 | 0.068 | 0.025 | **351** | 0.055 | 0.077 | 0.027 | **493** | 0.061 | 0.051 | 0.027 |
| **62** | 0.027 | 0.049 | 0.021 | **352** | 0.065 | 0.081 | 0.026 | **494** | 0.063 | 0.074 | 0.030 |
| **63** | 0.038 | 0.083 | 0.025 | **353** | 0.098 | 0.105 | 0.027 | **495** | 0.064 | 0.088 | 0.032 |
| **64** | 0.067 | 0.089 | 0.024 | **354** | 0.070 | 0.064 | 0.032 | **496** | 0.069 | 0.099 | 0.030 |
| **65** | 0.062 | 0.056 | 0.023 | **355** | 0.065 | 0.093 | 0.032 | **497** | 0.067 | 0.096 | 0.031 |
| **66** | - | - | - | **356** | 0.084 | 0.123 | 0.033 | **498** | 0.070 | 0.072 | 0.028 |
| **67** | - | - | - | **357** | 0.059 | 0.079 | 0.032 | **499** | 0.065 | 0.072 | 0.028 |
| **68** | - | - | - | **358** | 0.073 | 0.077 | 0.032 | **500** | 0.074 | 0.084 | 0.029 |
| **69** | - | - | - | **359** | 0.080 | 0.070 | 0.035 | **501** | 0.080 | 0.082 | 0.030 |
| **70** | 0.072 | 0.051 | 0.023 | **360** | 0.089 | 0.095 | 0.033 | **502** | 0.051 | 0.051 | 0.013 |
| **71** | 0.077 | 0.050 | 0.025 | **361** | 0.085 | 0.094 | 0.032 | **503** | 0.029 | 0.041 | 0.013 |
| **72** | 0.038 | 0.164 | 0.023 | **362** | 0.084 | 0.085 | 0.033 | **504** | 0.047 | 0.053 | 0.011 |
| **73** | 0.052 | 0.111 | 0.025 | **363** | 0.122 | 0.151 | 0.028 | **505** | 0.036 | 0.043 | 0.011 |
| **74** | 0.049 | 0.095 | 0.023 | **364** | 0.044 | 0.078 | 0.030 | **506** | 0.034 | 0.053 | 0.009 |
| **75** | 0.046 | 0.093 | 0.026 | **365** | 0.027 | 0.013 | 0.029 | **510** | 0.051 | 0.051 | 0.013 |
| **76** | 0.040 | 0.128 | 0.025 | **366** | 0.054 | 0.067 | 0.033 | **511** | 0.029 | 0.041 | 0.013 |
| **77** | 0.072 | 0.154 | 0.022 | **367** | 0.065 | 0.058 | 0.022 | **512** | 0.047 | 0.053 | 0.011 |
| **78** | 0.046 | 0.058 | 0.022 | **368** | 0.071 | 0.061 | 0.024 | **513** | 0.036 | 0.043 | 0.011 |
| **79** | 0.039 | 0.062 | 0.022 | **369** | 0.063 | 0.067 | 0.025 | **514** | 0.034 | 0.053 | 0.009 |
| **80** | 0.038 | 0.062 | 0.022 | **370** | 0.062 | 0.052 | 0.025 | **515** | 0.080 | 0.076 | 0.031 |
| **81** | 0.039 | 0.064 | 0.023 | **371** | 0.061 | 0.069 | 0.024 | **516** | 0.066 | 0.078 | 0.034 |
| **82** | 0.093 | 0.106 | 0.022 | **372** | 0.051 | 0.069 | 0.023 | **517** | 0.071 | 0.080 | 0.030 |
| **83** | 0.092 | 0.123 | 0.024 | **373** | 0.065 | 0.079 | 0.022 | **518** | 0.102 | 0.080 | 0.028 |
| **84** | 0.050 | 0.069 | 0.024 | **374** | 0.060 | 0.074 | 0.026 | **519** | 0.108 | 0.050 | 0.030 |
| **85** | 0.048 | 0.064 | 0.025 | **375** | 0.071 | 0.090 | 0.025 | **520** | 0.064 | 0.044 | 0.030 |
| **86** | 0.070 | 0.092 | 0.023 | **376** | 0.050 | 0.077 | 0.024 | **521** | 0.056 | 0.041 | 0.031 |
| **87** | 0.055 | 0.107 | 0.024 | **377** | 0.062 | 0.071 | 0.027 | **522** | 0.046 | 0.059 | 0.031 |
| **89** | 0.080 | 0.107 | 0.026 | **378** | 0.065 | 0.063 | 0.028 | **523** | 0.038 | 0.061 | 0.033 |
| **90** | 0.050 | 0.072 | 0.022 | **379** | 0.075 | 0.065 | 0.029 | **524** | 0.065 | 0.045 | 0.033 |
| **91** | 0.234 | 0.024 | 0.025 | **380** | 0.069 | 0.070 | 0.042 | **525** | 0.086 | 0.039 | 0.036 |
| **92** | 0.141 | 0.048 | 0.025 | **381** | 0.063 | 0.064 | 0.033 | **526** | 0.029 | 0.051 | 0.037 |
| **93** | 0.048 | 0.065 | 0.025 | **382** | 0.060 | 0.064 | 0.032 | **527** | - | - | 0.036 |
| **94** | 0.074 | 0.065 | 0.025 | **383** | 0.063 | 0.067 | 0.032 | **528** | 0.026 | 0.074 | 0.030 |
| **95** | 0.074 | 0.064 | 0.025 | **384** | 0.067 | 0.057 | 0.031 | **529** | 0.097 | 0.120 | 0.034 |
| **96** | 0.058 | 0.000 | 0.027 | **385** | 0.066 | 0.067 | 0.028 | **530** | 0.120 | 0.091 | 0.024 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **97** | 0.039 | 0.051 | 0.026 | **386** | 0.056 | 0.057 | 0.032 | **531** | 0.045 | 0.064 | 0.027 |
| **98** | 0.024 | 0.051 | 0.026 | **387** | 0.074 | 0.102 | 0.024 | **532** | 0.056 | 0.075 | 0.023 |
| **99** | 0.058 | 0.088 | 0.026 | **388** | 0.059 | 0.059 | 0.024 | **533** | 0.051 | 0.073 | 0.023 |
| **100** | 0.068 | 0.100 | 0.027 | **389** | 0.061 | 0.055 | 0.025 | **534** | 0.058 | 0.075 | 0.024 |
| **101** | 0.064 | 0.069 | 0.025 | **390** | 0.067 | 0.064 | 0.028 | **535** | 0.057 | 0.080 | 0.023 |
| **102** | 0.068 | 0.074 | 0.026 | **391** | 0.060 | 0.067 | 0.029 | **536** | 0.053 | 0.075 | 0.022 |
| **103** | 0.062 | 0.081 | 0.027 | **392** | 0.066 | 0.063 | 0.024 | **537** | 0.047 | 0.057 | 0.024 |
| **104** | 0.057 | 0.072 | 0.027 | **393** | 0.071 | 0.067 | 0.024 | **538** | 0.053 | 0.051 | 0.025 |
| **105** | 0.050 | 0.089 | 0.025 | **394** | 0.076 | 0.109 | 0.029 | **539** | 0.060 | 0.061 | 0.023 |
| **106** | 0.076 | 0.099 | 0.028 | **395** | 0.080 | 0.087 | 0.031 | **540** | 0.060 | 0.093 | 0.023 |
| **107** | 0.103 | 0.112 | 0.027 | **396** | 0.064 | 0.069 | 0.028 | **541** | 0.046 | 0.063 | 0.022 |
| **108** | 0.077 | 0.133 | 0.028 | **397** | 0.045 | 0.050 | 0.029 | **542** | 0.062 | 0.064 | 0.022 |
| **109** | 0.077 | 0.125 | 0.037 | **398** | 0.061 | 0.053 | 0.031 | **543** | 0.047 | 0.049 | 0.024 |
| **110** | 0.064 | 0.067 | 0.032 | **399** | 0.070 | 0.085 | 0.034 | **544** | 0.050 | 0.062 | 0.023 |
| **111** | 0.069 | 0.116 | 0.027 | **400** | 0.094 | 0.083 | 0.031 | **545** | 0.058 | 0.084 | 0.024 |
| **112** | 0.079 | 0.121 | 0.026 | **401** | 0.058 | 0.061 | 0.032 | **546** | 0.060 | 0.074 | 0.023 |
| **113** | 0.043 | 0.033 | 0.028 | **402** | 0.054 | 0.051 | 0.031 | **547** | 0.055 | 0.069 | 0.023 |
| **114** | 0.027 | 0.014 | 0.028 | **403** | 0.079 | 0.075 | 0.029 | **548** | 0.052 | 0.066 | 0.023 |
| **115** | 0.046 | 0.035 | 0.068 | **404** | 0.083 | 0.068 | 0.031 | **549** | 0.057 | 0.063 | 0.023 |
| **116** | 0.029 | 0.116 | 0.065 | **405** | 0.068 | 0.065 | 0.030 | **550** | 0.058 | 0.075 | 0.022 |
| **117** | 0.130 | 0.052 | 0.028 | **406** | 0.034 | 0.080 | 0.024 | **551** | 0.060 | 0.075 | 0.022 |
| **118** | 0.076 | 0.037 | 0.029 | **407** | 0.050 | 0.083 | 0.026 | **552** | 0.062 | 0.068 | 0.018 |
| **119** | 0.034 | 0.062 | 0.033 | **408** | 0.057 | 0.080 | 0.027 | **553** | 0.058 | 0.085 | 0.028 |
| **120** | 0.055 | 0.110 | 0.026 | **409** | 0.066 | 0.063 | 0.024 | **554** | 0.057 | 0.076 | 0.028 |
| **121** | 0.126 | 0.084 | 0.028 | **410** | 0.076 | 0.070 | 0.027 | **555** | 0.072 | 0.074 | 0.025 |
| **122** | 0.129 | 0.108 | 0.029 | **411** | 0.020 | 0.069 | 0.024 | **556** | 0.062 | 0.065 | 0.024 |
| **123** | 0.101 | 0.083 | 0.029 | **412** | 0.020 | 0.074 | 0.026 | **557** | 0.069 | 0.070 | 0.023 |
| **259** | 0.068 | 0.094 | 0.028 | **413** | 0.009 | 0.090 | 0.028 | **558** | 0.081 | 0.079 | 0.022 |
| **260** | 0.070 | 0.094 | 0.028 | **414** | 0.095 | 0.046 | 0.025 | **559** | 0.080 | 0.108 | 0.023 |
| **261** | 0.059 | 0.059 | 0.027 | **415** | 0.082 | 0.070 | 0.026 | **560** | 0.048 | 0.059 | 0.021 |
| **262** | 0.079 | 0.079 | 0.029 | **416** | 0.052 | 0.059 | 0.026 | **561** | 0.042 | 0.064 | 0.023 |
| **263** | 0.074 | 0.126 | 0.030 | **417** | 0.035 | 0.034 | 0.029 | **562** | 0.057 | 0.072 | 0.023 |
| **264** | 0.084 | 0.100 | 0.030 | **418** | 0.062 | 0.088 | 0.025 | **563** | 0.042 | 0.075 | 0.023 |
| **266** | 0.062 | 0.064 | 0.030 | **419** | 0.052 | 0.068 | 0.026 | **564** | 0.060 | 0.079 | 0.022 |
| **267** | 0.092 | 0.072 | 0.031 | **420** | 0.057 | 0.071 | 0.027 | **565** | 0.054 | 0.068 | 0.023 |
| **268** | 0.074 | 0.092 | 0.030 | **421** | 0.064 | 0.089 | 0.025 | **566** | 0.061 | 0.081 | 0.023 |
| **269** | 0.063 | 0.079 | 0.031 | **422** | 0.059 | 0.102 | 0.027 | **567** | 0.061 | 0.077 | 0.021 |
| **270** | 0.065 | 0.078 | 0.029 | **423** | 0.062 | 0.106 | 0.026 | **568** | 0.050 | 0.060 | 0.022 |
| **271** | 0.071 | 0.074 | 0.033 | **424** | 0.035 | 0.096 | 0.029 | **569** | 0.047 | 0.056 | 0.023 |
| **272** | 0.057 | 0.091 | 0.030 | **425** | 0.061 | 0.057 | 0.028 | **570** | 0.048 | 0.054 | 0.024 |
| **273** | 0.060 | 0.098 | 0.033 | **426** | 0.061 | 0.069 | 0.028 | **571** | 0.057 | 0.086 | 0.024 |
| **274** | 0.066 | 0.086 | 0.028 | **427** | 0.091 | 0.078 | 0.027 | **750** | 0.047 | 0.109 | 0.023 |
| **275** | 0.069 | 0.073 | 0.027 | **428** | 0.077 | 0.059 | 0.028 | **751** | 0.054 | 0.095 | 0.023 |
| **276** | 0.055 | 0.060 | 0.030 | **429** | 0.097 | 0.073 | 0.029 | **752** | 0.055 | 0.089 | 0.023 |
| **277** | 0.055 | 0.068 | 0.028 | **430** | 0.122 | 0.077 | 0.027 | **753** | 0.052 | 0.072 | 0.022 |
| **278** | 0.067 | 0.081 | 0.034 | **431** | 0.086 | 0.044 | 0.030 | | | | |

Table 5: Average Magnitudes by Line (Feet)

| Category | X | Y | Z |
|---|---|---|---|
| **Average Magnitude** | 0.062 | 0.075 | 0.026 |
| **RMS Values** | 0.094 | 0.115 | 0.036 |
| **Maximum Values** | 0.492 | 0.496 | 0.479 |
| **Observation Weight** | 55060.0 | 55060.0 | 935169.0 |

Table 6: Internal Observation Statistics (Feet)

| Category | Mismatch |
|---|---|
| **Average 3D Mismatch** | 0.03148 |
| **Average XY Mismatch** | 0.11446 |
| **Average Z Mismatch** | 0.02599 |

Table 7: Overall Relative Accuracy (Feet)

| Category | Observations |
|---|---|
| **Section Lines** | 361,746 |
| **Roof Lines** | 25,431 |

Table 8: Vector Observations

## 3.4 Lidar Classification

Lidar filtering was accomplished using GeoCue with TerraSolid processing and modeling software. The filtering process reclassifies all the data into classes within the point cloud classification scheme. Once the data is classified, the entire dataset is reviewed and manually edited for anomalies that are outside the required guidelines of the product specification or contract requirements. This can include, but is not limited to, classifying bridges, structures, filling culverts, and manually analyzing the bare-earth surface by classifying features that belong in non-extraneous classification codes. **Table 9** outlines a statistical summary of the point classes leveraged in the lidar dataset.

| Code | Class | Points |
|---|---|---|
| **1** | Unclassified | 117,493,756,289 |
| **2** | Ground | 104,639,014,861 |
| **7** | Low Noise | 858,095,991 |
| **9** | Water | 14,757,915 |
| **17** | Bridge Decks | 399,685 |
| **18** | High Noise | 1,767,946,813 |
| **Flag** | Withheld | 2,626,042,804 |

Table 9: Lidar Classification Statistics

## 3.5 Accuracy Assessment

The lidar dataset was evaluated using a total of four-hundred and fifteen (415) check points (244 NVA + 171 VVA). The result provided a vertical accuracy that fell within project specifications. Please see the **Attachment A** for the full Vertical Accuracy Report and the project *Metadata* for an in-depth accuracy assessment. **Table 10** outlines the absolute accuracy requirements of the project. **Table 11** shows high level statistics and mean errors for the area processed by Sanborn.

| Category | Value (m) | Value (ft) |
|---|---|---|
| RMSEz | ≤0.100 | ≤0.328 |
| @ 95-Percent Confidence Level | ≤0.196 | ≤0.643 |
| @ 95th Percentile | ≤0.300 | ≤0.984 |

Table 10: Absolute Accuracy Requirements

| Broad Land Cover Type | # of Points | RMSEz | 95% Confidence Level | 95th Percentile |
|---|---|---|---|---|
| **NVA of Point Cloud** | 244 | 0.198 | 0.389 | |
| **NVA of Bare Earth** | 244 | 0.201 | 0.393 | |
| **NVA of DEM** | 244 | 0.201 | 0.394 | |
| **VVA of Bare Earth** | 171 | 0.241 | | 0.478 |
| **VVA of DEM** | 171 | 0.244 | | 0.465 |

Table 11: Vertical Accuracy Assessment of Check Points (Feet)

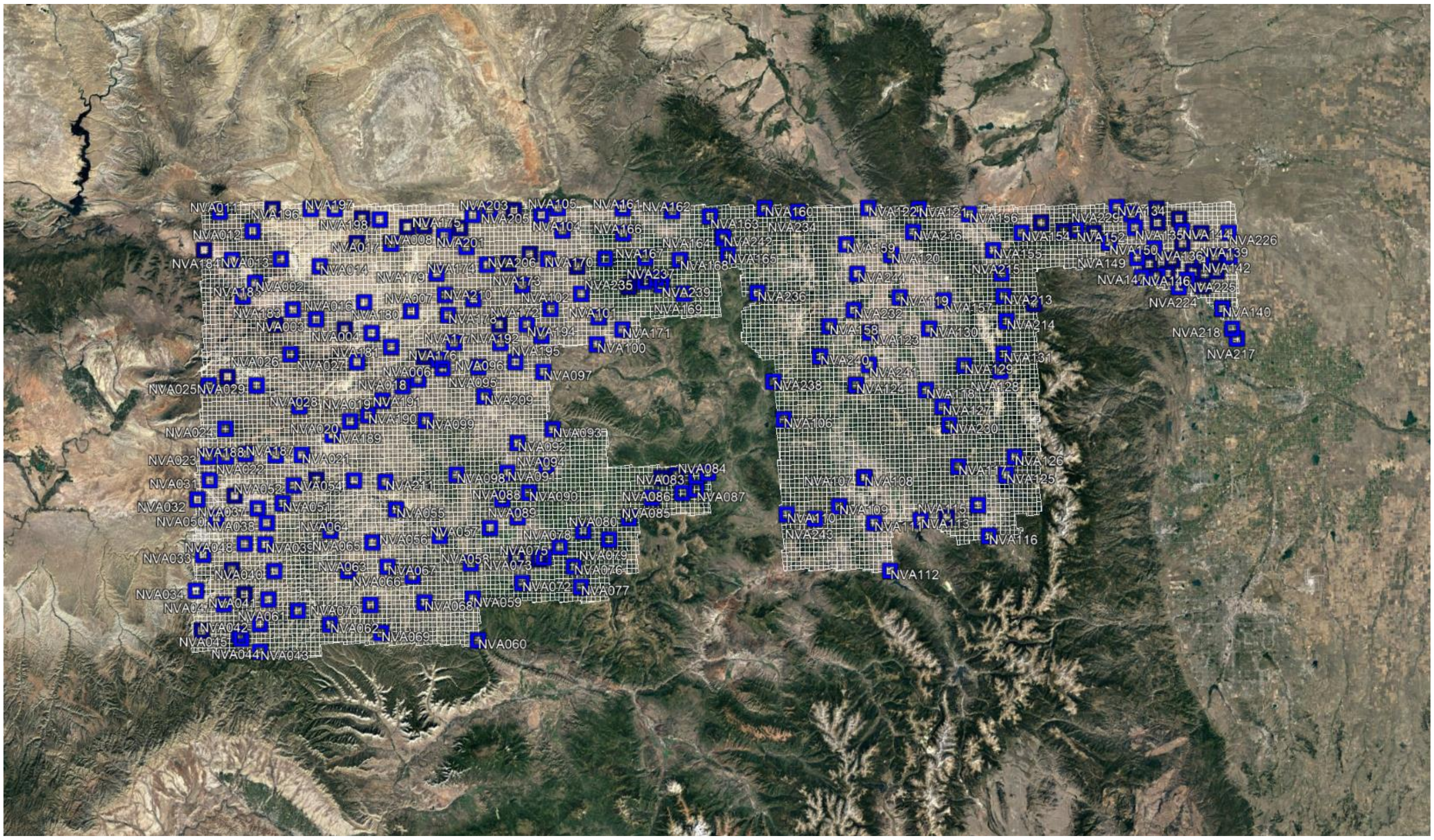



Figure 7: Non-vegetated Check Point Distribution

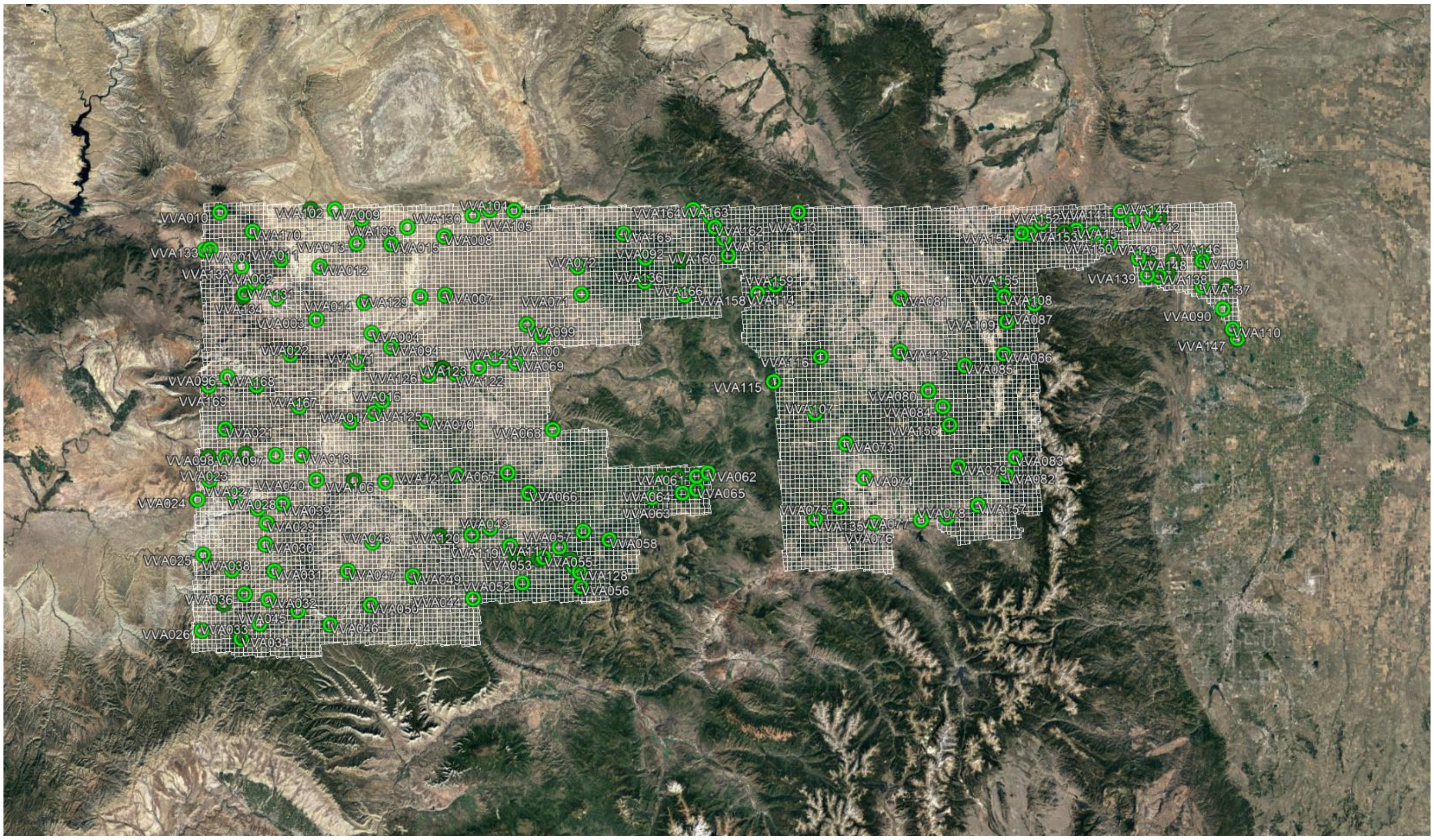


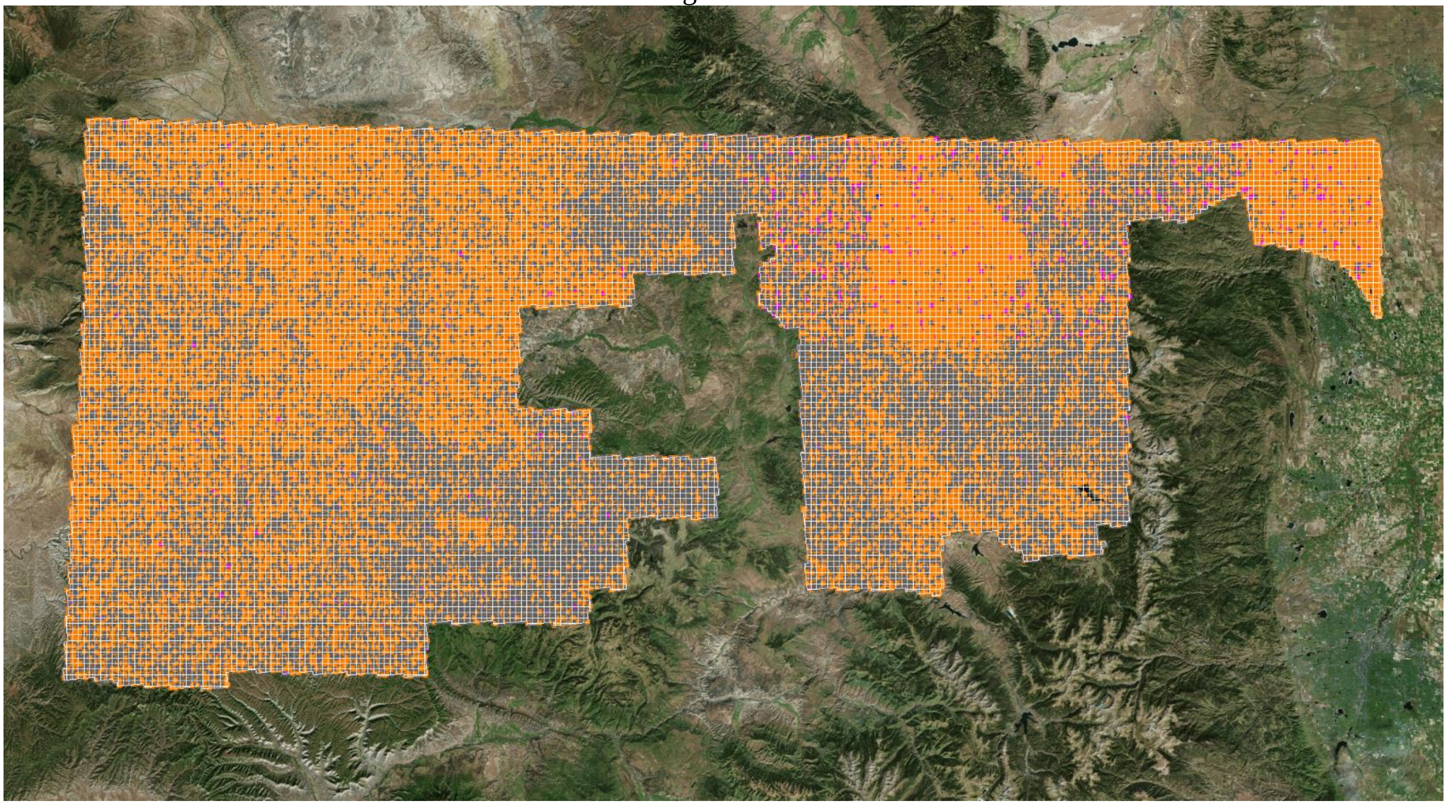
Figure 8: Vegetated Check Point Distribution

# 4.0 PRODUCT GENERATION

The following products were generated using the final coordinate system as defined in the contract:

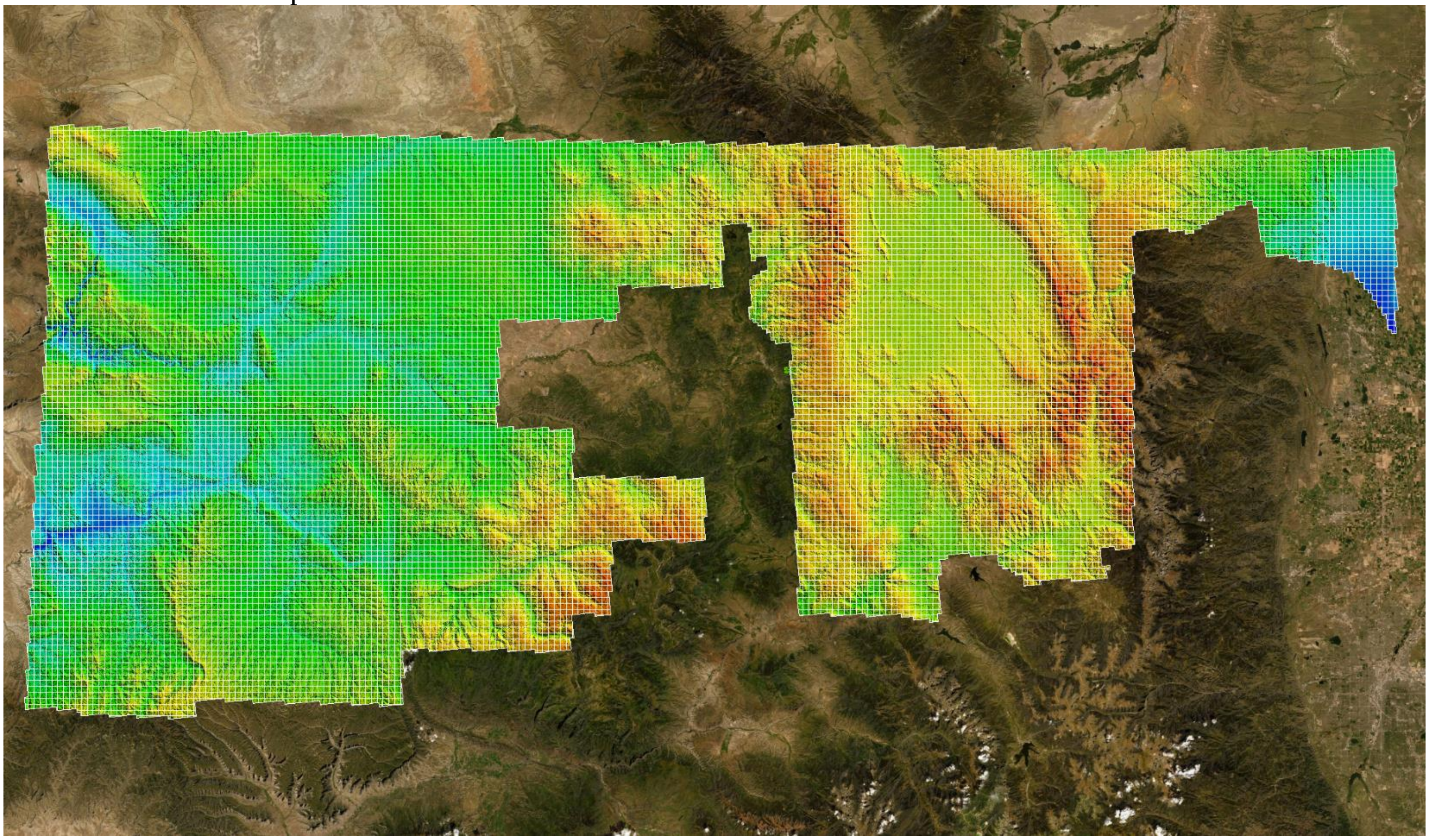
## Classified Point Cloud

The Classified Point Cloud, containing all returns, is delivered in LAZv1.4 (*.laz) format and meets project specifications. The Classified Point Cloud contains file names referencing the tile index.



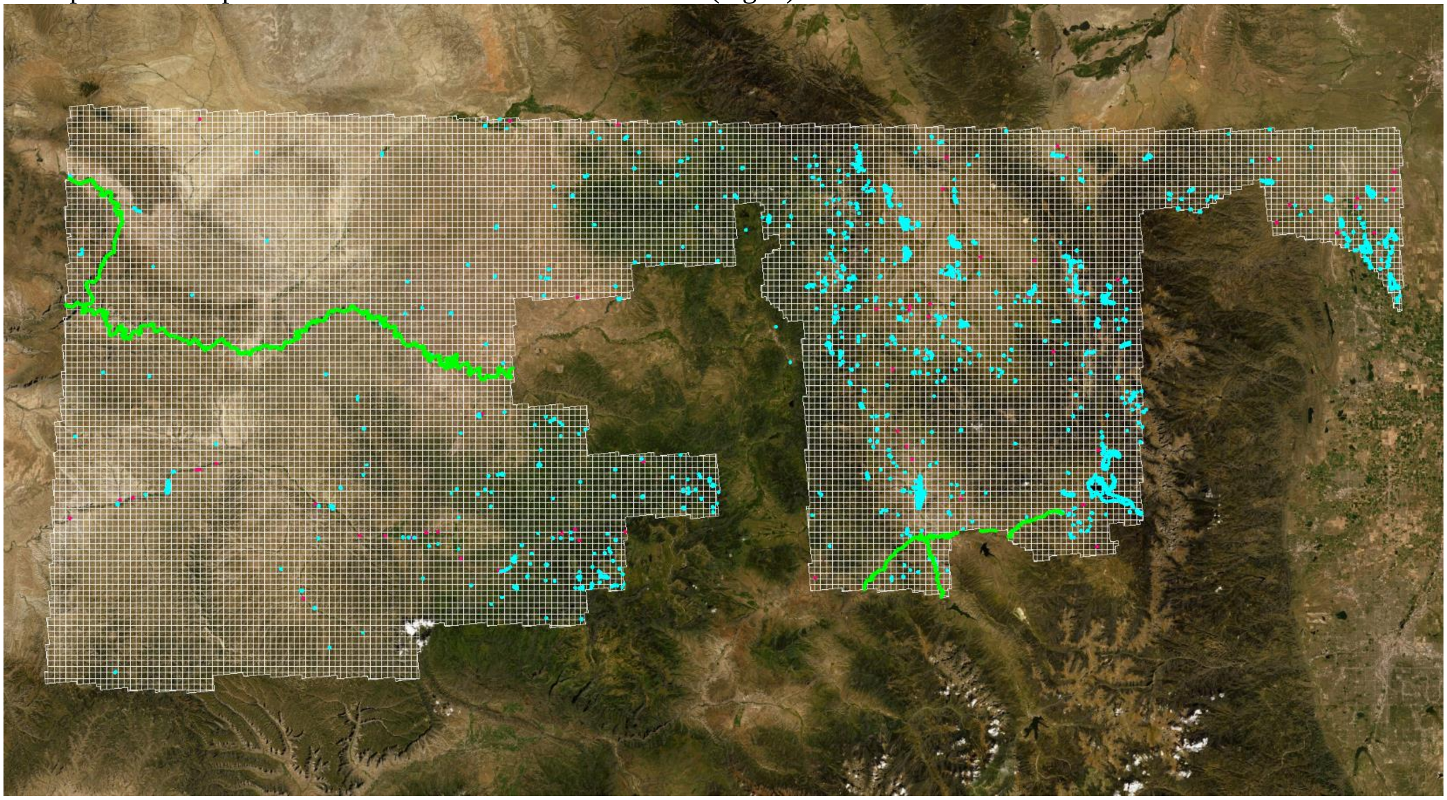
## Bare-earth Digital Elevation Model (DEM)

32-bit GeoTIFF (*.tif) elevation rasters were created from the bare-earth points in the processed lidar dataset and hydro-flattened breaklines. Bare-earth rasters were produced the bilinear interpolation methodology and GDAL v2.4.0 was used to define the CRS. Each pixel contains an elevation.



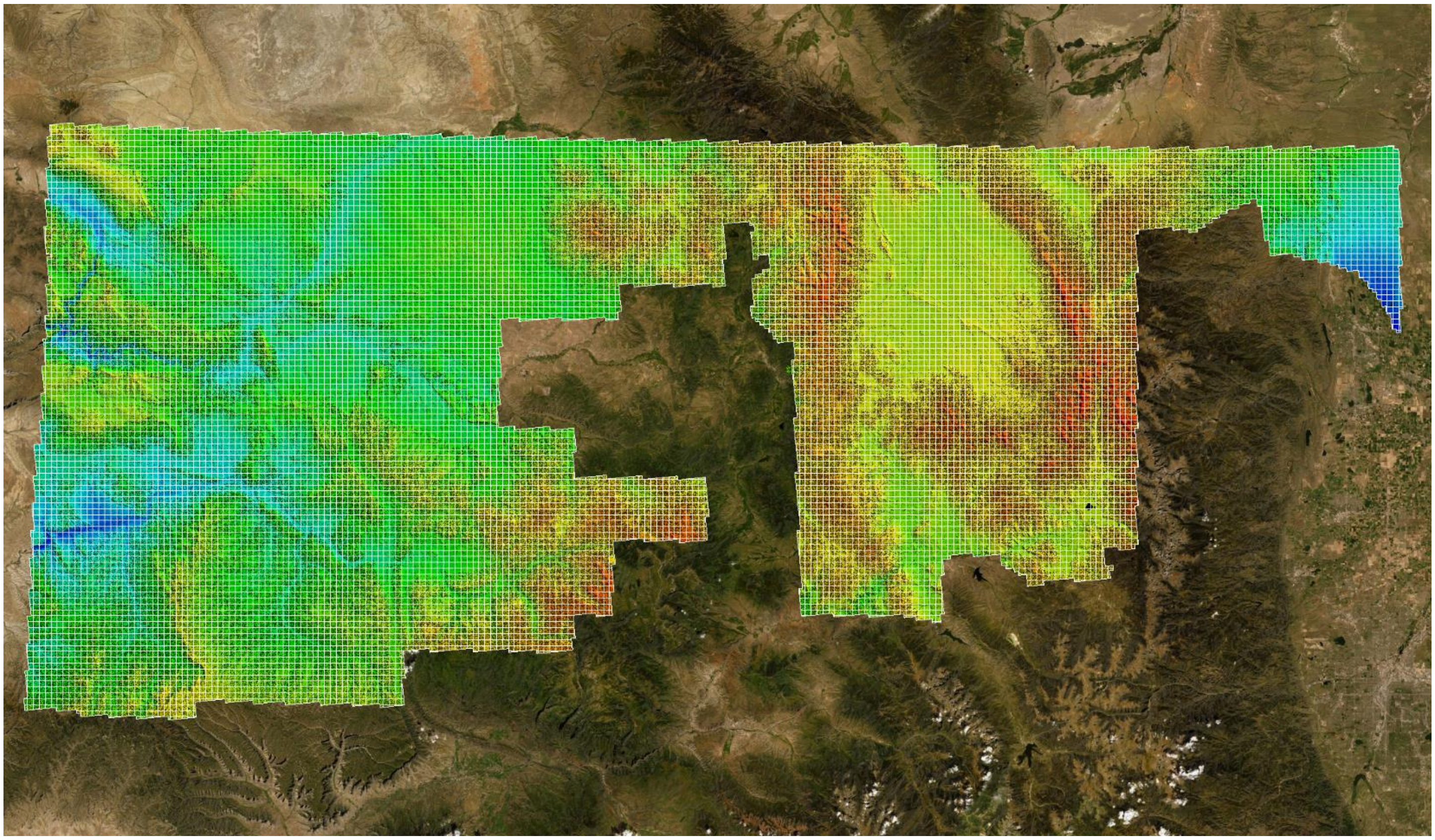
## Breaklines

Hydro-flattened breaklines were generated from digitized water features conflated to the elevations derived from the bare-earth points in the processed lidar dataset. Delivered in Esri (*.gdb) format.



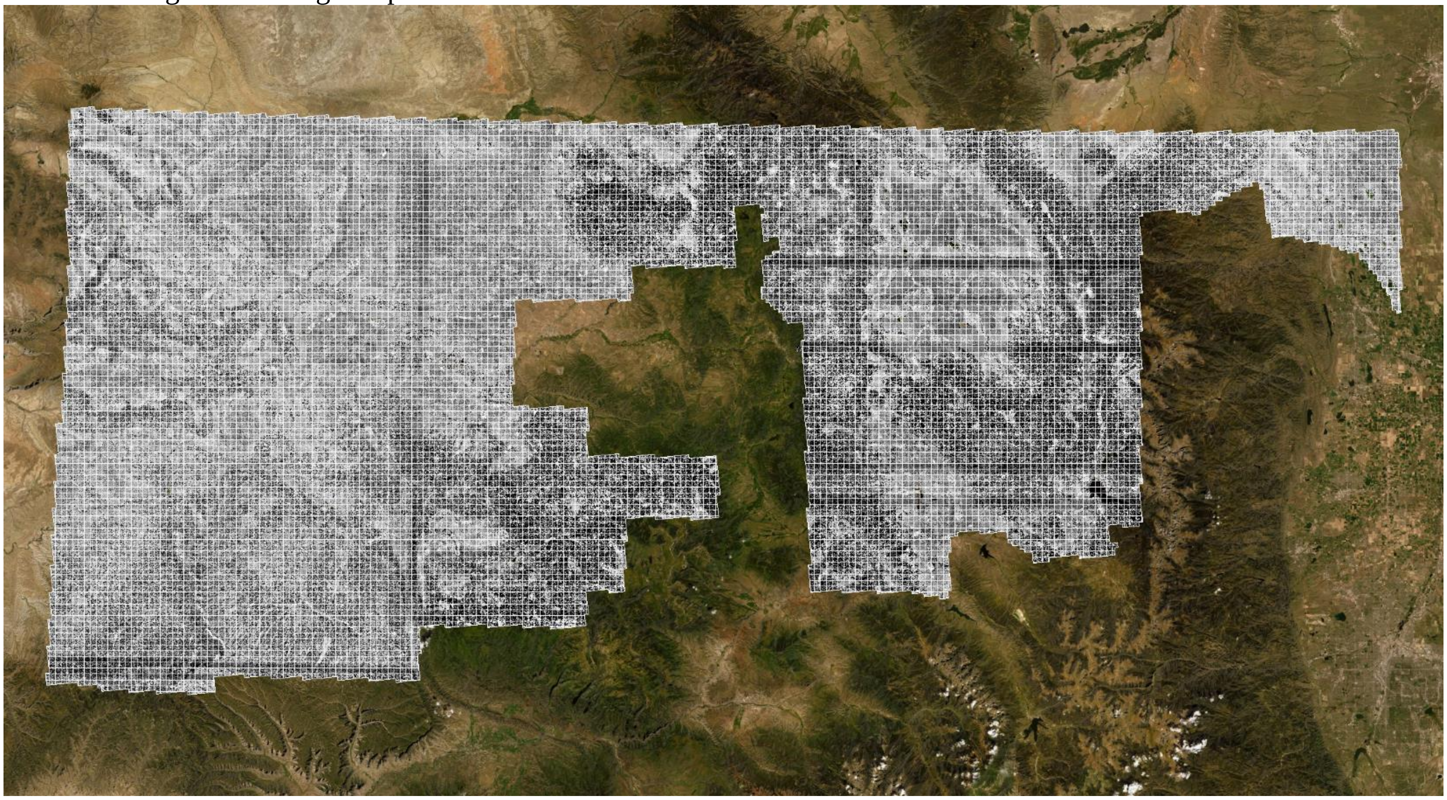
## Maximum Surface Height Raster (MSHR)

32-bit GeoTIFF (*.tif) elevation rasters were created from the maximum height points in the processed lidar dataset. Rasters were produced the bilinear interpolation methodology and GDAL v2.4.0 was used to define the CRS. Each pixel contains an elevation.



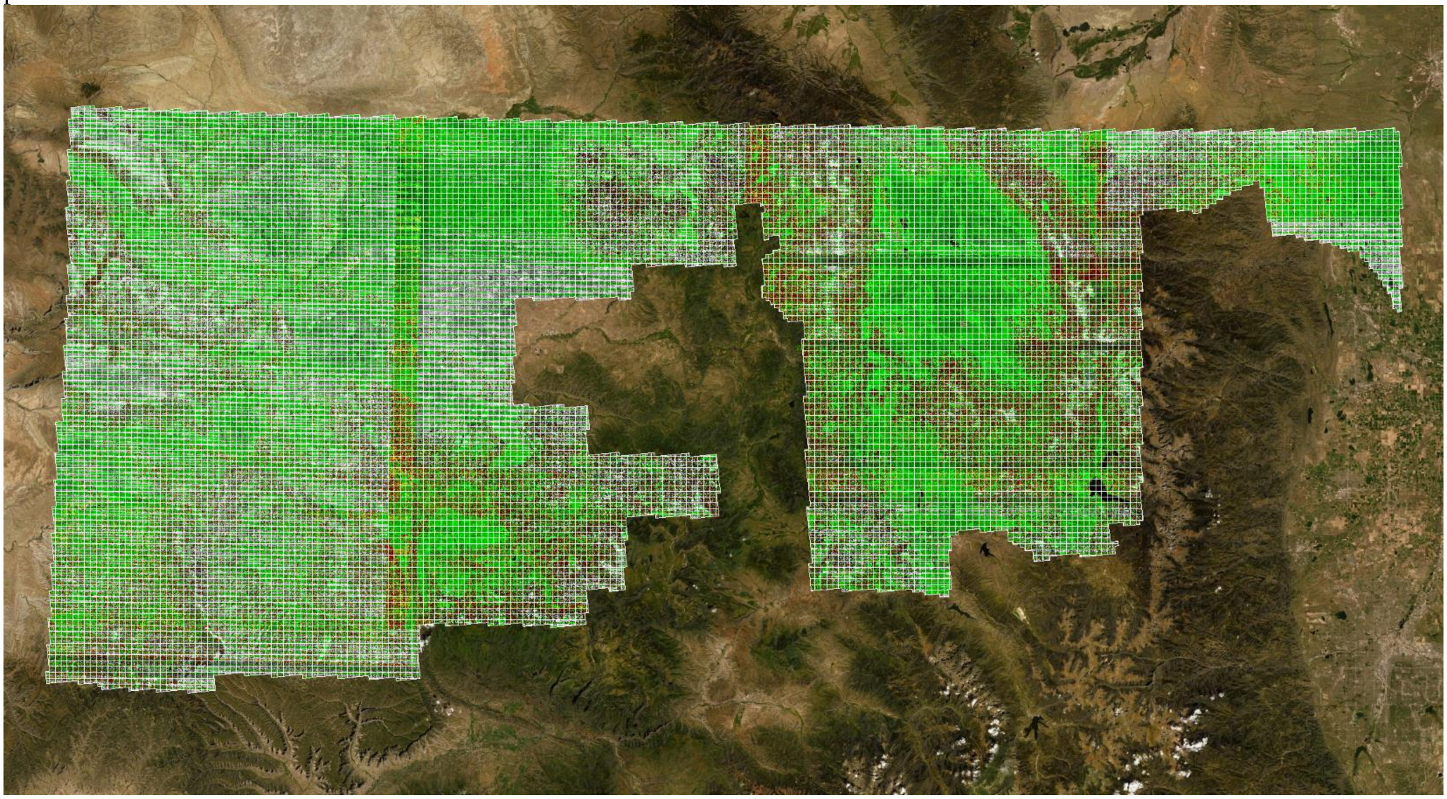
## First-return Intensity Images

8-bit GeoTIFF (*.tif) intensity rasters were created from the first-return points in the processed lidar dataset. All overlap classes were ignored during this process. GDAL v2.4.0 was used to define the CRS.



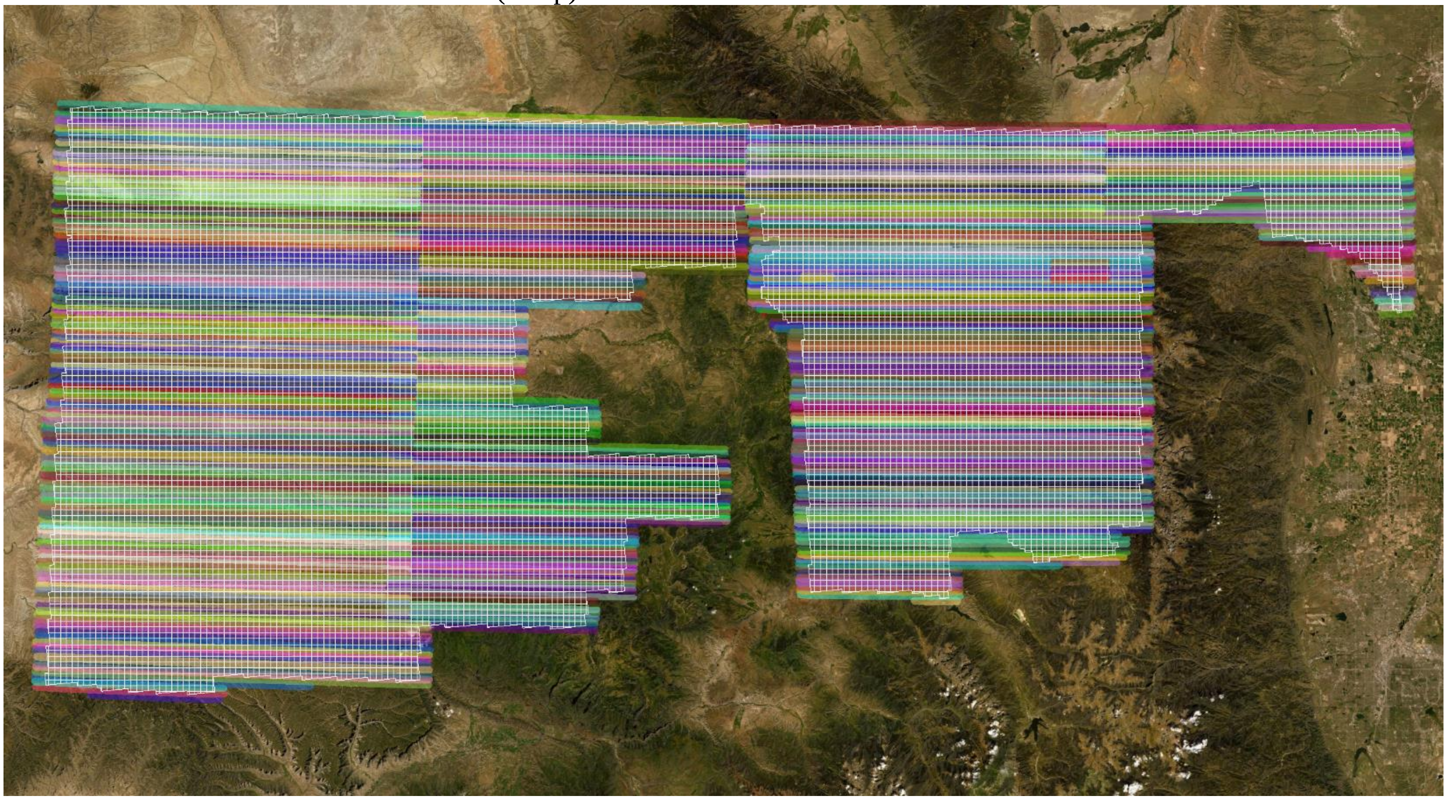
## Last-return Swath Separation Images

24-bit GeoTIFF (*.tif) swath separation images modulated by intensity were created from the last-return points in the processed lidar dataset. GDAL v2.4.0 was used to define the CRS.



## Swath Polygons

Polygons features representing either the convex or concave hull of swaths, where each record is an individual swath or channel within a swath. Delivered in Esri (*.shp) format.



## Other Deliverables

Metadata
Vertical Accuracy Report

A final quality assurance process was undertaken to validate all deliverables for the project. Prior to release of data for delivery, Sanborn's Quality Control/Quality Assurance department reviews the data and then releases it for delivery.