Lidar Mapping Report for the U.S. Geological Survey

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WOOLPERT

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Attachment 1: Flight Logs
Attachment 2: SBET and POSPac Reports

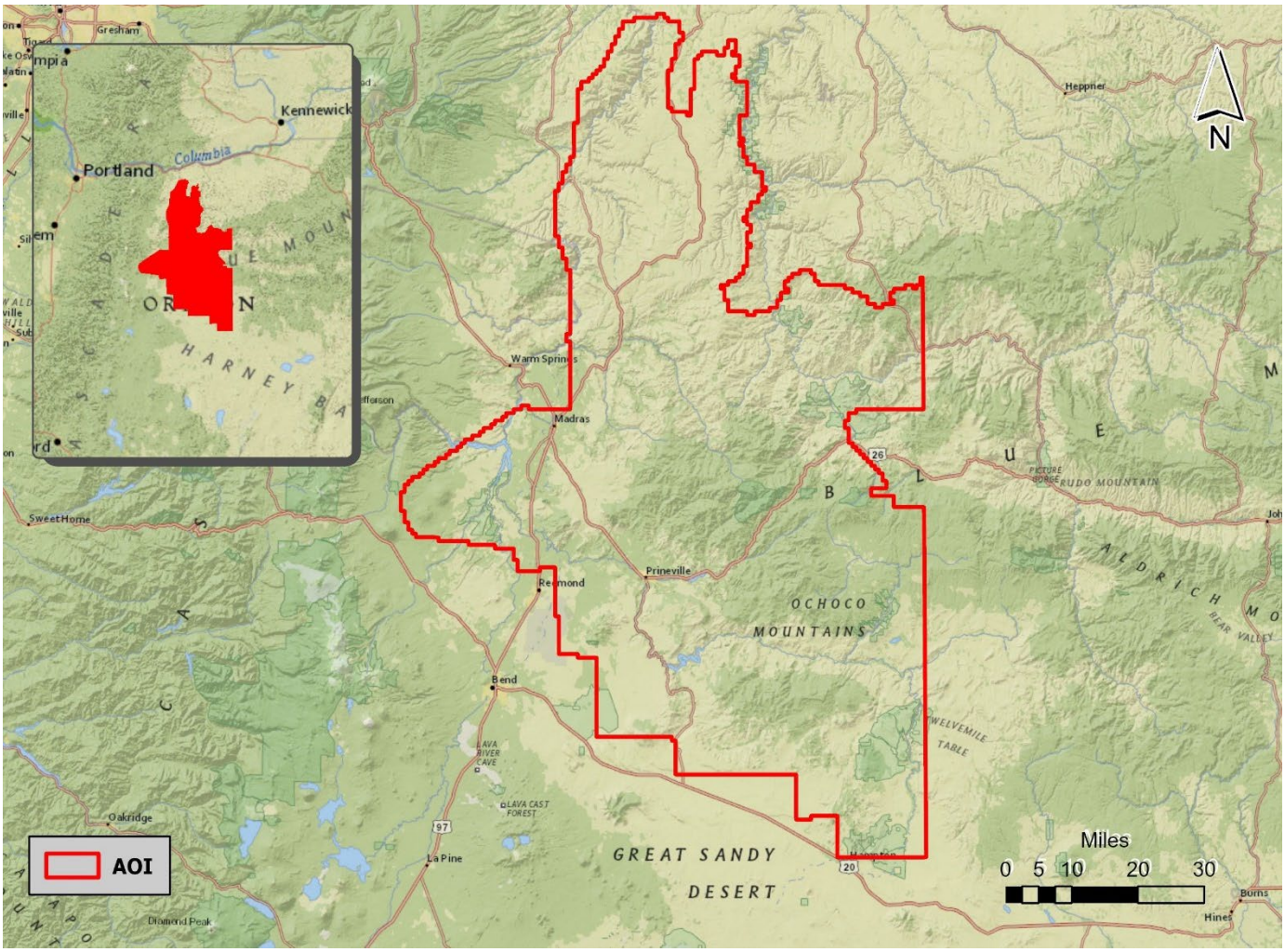
1. Overview

1.1. Description

OR_SouthEast_12_D22, WU300579 is part of Task order 140G0222F0211.

This Lidar Mapping Report will cover the acquisition, processing, and derivative products of Work Unit 300579. Lidar data was collected to an aggregate nominal pulse spacing (ANPS) of ≤0.35 and 8-points per square meter (ppsm) covering 5,256 square miles in Oregon 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 Geospatial, under supervision by Woolpert.

Figure 1. OR_SouthEast_12_D22



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* v2023 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 10
- Horizontal Units: Meters
- Horizontal EPSG Code: 6339
- 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 1,000-meters x 1,000-meters. The delivery tiles are named in accordance with the US National Grid convention. This delivery's tiled dataset contains a total of 14,010 tiles.

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
    - Class 22 – Temporal Exclusion
- Breaklines used for hydro-flattening:
    - Rivers 30.5-meters / 100-feet and greater in width as PolylineZ features in Esri geodatabase format
    - Waterbodies greater than 2-acres as PolygonZ feature classes in Esri geodatabase format
    - Bridges used in DEM generation 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
- Maximum Surface Height Rasters (MSHR): 1-meter pixel Maximum Surface Height Rasters using all data points (not including withheld points) will be delivered in tiled GeoTIFF format
- Swath Separation Images: Swath Separation Images use only last return points (not including

withheld points) representing the geometry, intraswath alignment, and intensity of the point cloud data for each delivered block of data.

1.5.2. Metadata

- Tile index: 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, 32-bit floating-point, GeoTIFF format
- Swath separation images: 1-meter, GeoTIFF format.
- Temporal polygons
- Lidar Mapping Report in PDF Format
- Product level xml metadata.

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.

1.7. Lidar Sensor Information

Aerial lidar data was acquired using the Riegl VQ1560ii, VQ1560iiS and Galaxy T2000 lidar sensor systems.

1.7.1. Riegl VQ1560ii 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

Laser Specifications

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

Accuracy

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

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

1.7.2. Riegl VQ1560iiS 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

Laser Specifications

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

Sensor Accuracy

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

Physical Specifications

- Scanner size: 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

1.7.3. Galaxy T2000 Specifications

- Performance envelope: 150-6500 m AGL, nominal
- Position and orientation system: POS AV™ AP60 (OEM); 220-channel dual frequency GNSS receiver; GNSS airborne antenna with Iridium filters; high-accuracy AIMU (Type 57); non-ITAR
- Scan angle (FOV): 10-60°
- Swath width: 10-115% of altitude AGL
- Scan frequency: Maximum 160 Hz (320 scan lines/sec)

- Flight management system: Optech FMS (Airborne Mission Manager and Nav) with operator console
- Data storage: Removable SSD (primary); internal SSD (spare)
- Power requirements: 28 V; 400 W

Laser Specification

- Topographic laser: 1064-nm near-infrared
- Laser classification: Class IV (US FDA 21 CFR 1040.10 and 1040.11; IEC/EN 60825-1)
- Pulse repetition frequency (effective): Programmable, 100-2000 kHz
- Beam divergence: 0.16 mrad (1/e) or 0.23 mrad (1/e2)
- Laser range precision: 5 < 0.008 m, 1 σ

Accuracy

- Absolute horizontal accuracy: 1/10,000 × altitude; 1 σ
- Absolute elevation accuracy: < 0.03-0.25 m RMSE from 150-6500 m AGL

Physical Specifications

- Sensor: 0.34 × 0.34 × 0.25 m, 27 kg — PDU: 0.42 × 0.33 × 0.10 m, 6.5 kg
- Operating temperature: 0 to +35°C

1.8. Planned Flight Specifications

Aerial lidar data was acquired for this project using the following lidar sensor systems:

1.8.1. Riegl VQ1560ii – SN4890

- Maximum Number of Returns: 15
- Nominal Point Spacing: 0.35-m
- Nominal Point Density: 8 ppsm
- Flying Height Above Ground Level: 2,000-m
- Flight Speed: 145-knots
- Scan Angle: 58.5°
- Scan Rate Used: 342 lps
- Pulse Rate Used: 2x1400-kHz
- Multi-Pulse in Air: 1
- Overlap: Minimum 20%

1.8.2. Riegl VQ1560iiS – SN3061, SN3546, and SN4046

- Maximum Number of Returns: 15
- Nominal Point Spacing: 0.35-m
- Nominal Point Density: 8 ppsm
- Flying Height Above Ground Level: 1,600-m
- Flight Speed: 150-knots
- Scan Angle: 58.5°

- Scan Rate Used: 304 lps
- Pulse Rate Used: 2x1143-kHz
- Multi-Pulse in Air: 1
- Overlap: Minimum 20%

1.8.3. Optech Galaxy T2000

- Maximum Number of Returns: 8
- Nominal Point Spacing: 0.35-m
- Nominal Point Density: 8 ppsm
- Flying Height Above Ground Level: 1,645-m
- Flight Speed: 135-knots
- Scan Angle: 40
- Scan Rate: 95
- Pulse Rate Used: 1100-kHz
- Multi-Pulse in Air: 1
- Overlap: Minimum 30%

1.9. Timeline

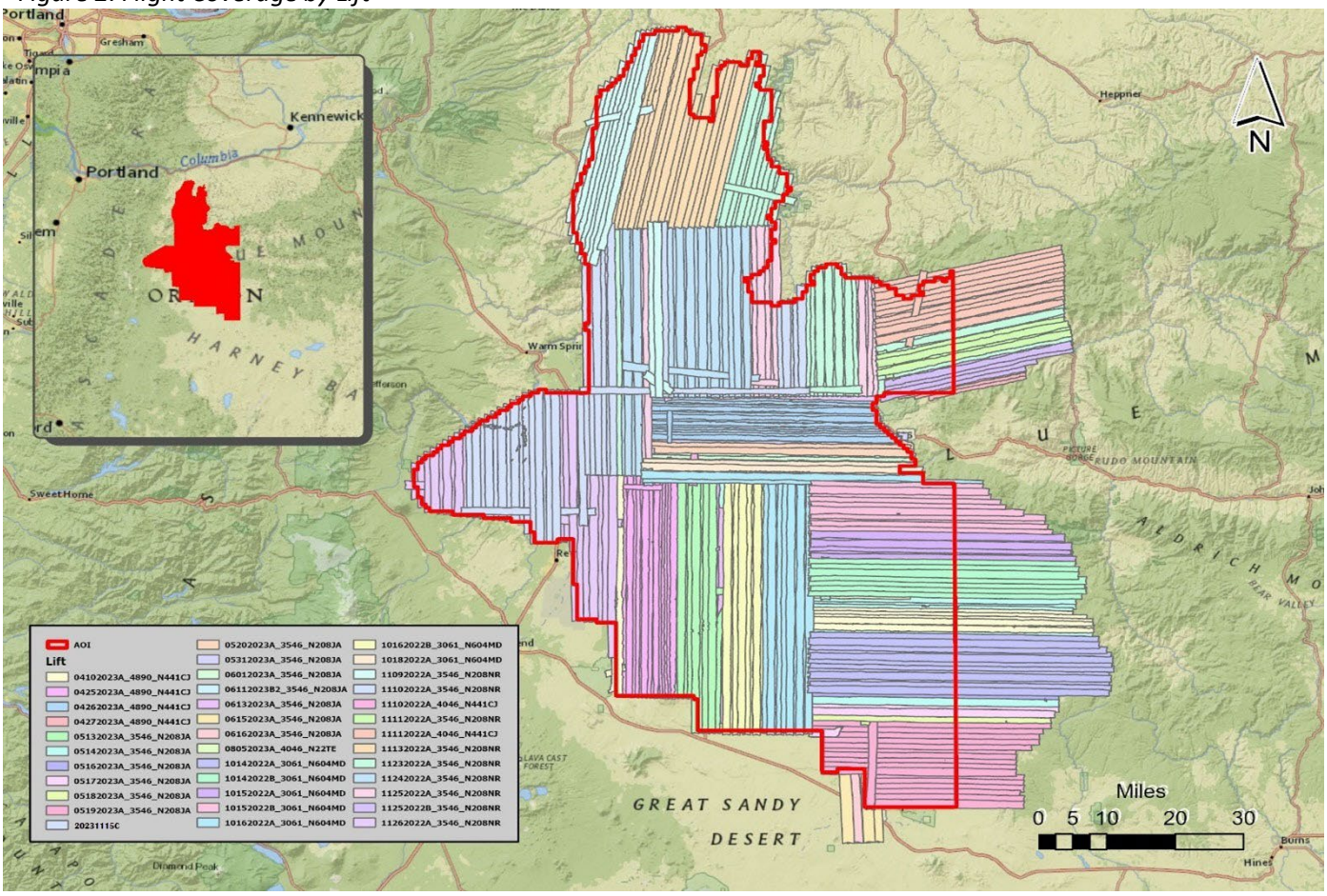
Lidar data was collected from October 14, 2022, through November 15, 2023. Flight logs are contained in Attachment 1: Flight Logs.

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.

Figure 2. Flight Coverage by Lift



1.11. Acquisition Quality Assurance

NV5 Geospatial uses a combination of off-the-shelf and internal proprietary software packages 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. NV5 Geospatial's 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.

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 in flightline swath format 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. Each flightline swath point cloud was calibrated using Strip Align software that corrects systematic geometric errors and improves the relative and absolute accuracy of the flightline swath point cloud. The calibrated point cloud swaths were imported into GeoCue distributive processing software, and the imported data was then tiled so further processing could take place in TerraScan software. Using TerraScan, the vertical accuracy of the surveyed ground control was tested, and any vertical bias was removed from the data. TerraScan and TerraModeler software packages were then used for automated data classification and manual cleanup. The data were manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler.

DEMs were then generated using proprietary software. In the bare earth surface model, above-ground features are excluded from the data set. Global Mapper is used as a final check of the bare earth dataset.

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

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. 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.

The calibrated data were automatically classified to the classification scheme using routines within the TerraScan software. After automated classification, the data were then manually reviewed using TerraScan and TerraModeler software packages to remove any remaining artifacts from the bare earth class (ASPRS Class 2). Bridge breaklines were 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.

2.3. Relative Accuracy: Interswath (Overlap) Consistency

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 2,000 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.019 meters, this data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 12.6 (cm) RMSEh Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 22 cm at a 95% confidence level.

2.4. Relative Accuracy: Intraswath Precision

Intraswath precision (smooth surface precision) was performed on hard surfaces with areas consisting of approximately 100-pixels (ex.: parking lots, large rooftops) and containing only single return lidar points. Sample areas were selected where full width of the swath(s) (left, center, and right) were represented to the extent the data allowed. The intraswath precision results were produced as polygon features in Esri shapefile format.

This project required the intraswath accuracy to meet ≤ 6-cm RMSDz. Accuracy was assessed in accordance with the "*USGS Base Specification v2023, Revision A*".

Precision = Range – (Slope x Cellsize x 1.414)

Range – Is the difference between the highest and lowest lidar points in each cell
Slope – is the maximum slope of the cell to its 8 neighbors
Cellsize – is set to the ANPS, rounded up to the next integer, and then doubled

NV5 Geospatial calculated the RMSDz to be 1.9 cm, minimum slope-corrected range to be 0.06 cm, and the maximum slope-corrected range to be 5.4 cm.

2.6 Lidar Data Classification

LAS The classification classes are determined by Lidar Base Specifications 2022 Rev. A and are an industry standard for the classification of lidar point clouds.

All data was manually reviewed and any remaining artifacts were removed. Industry-standard LAS files were then created. 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: Default / Processed, but not Classified
- Class 2: Bare Earth Ground
- 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. Temporal Exclusion (Class 22) was used to classify hydro points to different water elevations between flight lines and to classify snow that was present in one flight line and not

the other, which precludes us from using snow class because it would cause issues with the surface. The snow polygons contain the areas where the temporal exclusion class was used to denote snow in a flight line, and the temporal polygons contain the hydro areas.

2.7 Hydrologic Flattening

The 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 NV5 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 shapefile, clipped to the project boundary, and imported into an Esri file geodatabase for delivery.

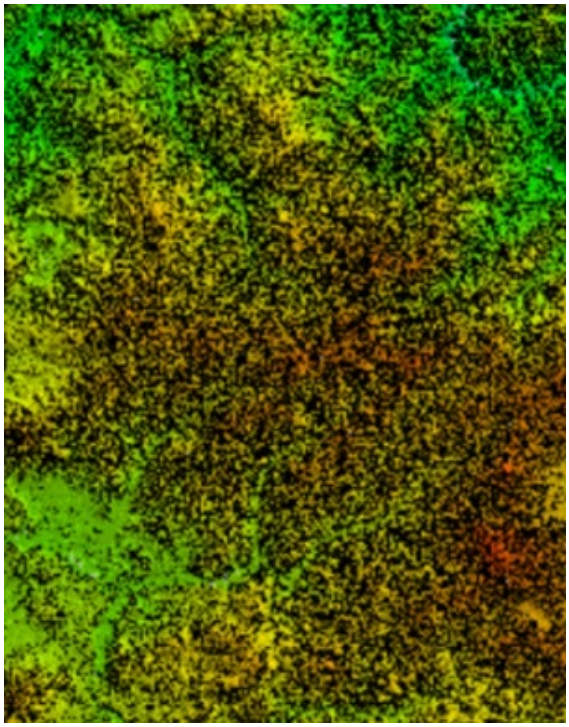
2.8 Digital Elevation Model

Hydro-Flattened DEMs (topographic) represent a lidar-derived product illustrating the grounded terrain and associated breaklines (as described above) in raster form. NV5 Geospatial's 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. NV5 Geospatial's 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. NV5 Geospatial ensures there are no void or no-data values (-999999) in each derived DEM. This is achieved by using propriety software checking all cell values that fall within the project boundary. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

2.9 Maximum Surface Height Raster Processing

Maximum Surface Height Rasters were produced as ancillary data from the classified lidar point cloud in order to evaluate the withheld bit flag proof of performance for points that cannot be reasonably interpreted as valid surface returns. These were produced using all returns, withheld flagged points excluded, and using the highest elevation point value from each pixel. These rasters are 32-bit, floating point format and delivered as GeoTIFF files per tile.

Figure 3. Maximum Surface Height Raster



2.10 Swath Separation Image

The 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. NV5 Geospatial proprietary software generated 1-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. 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.

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

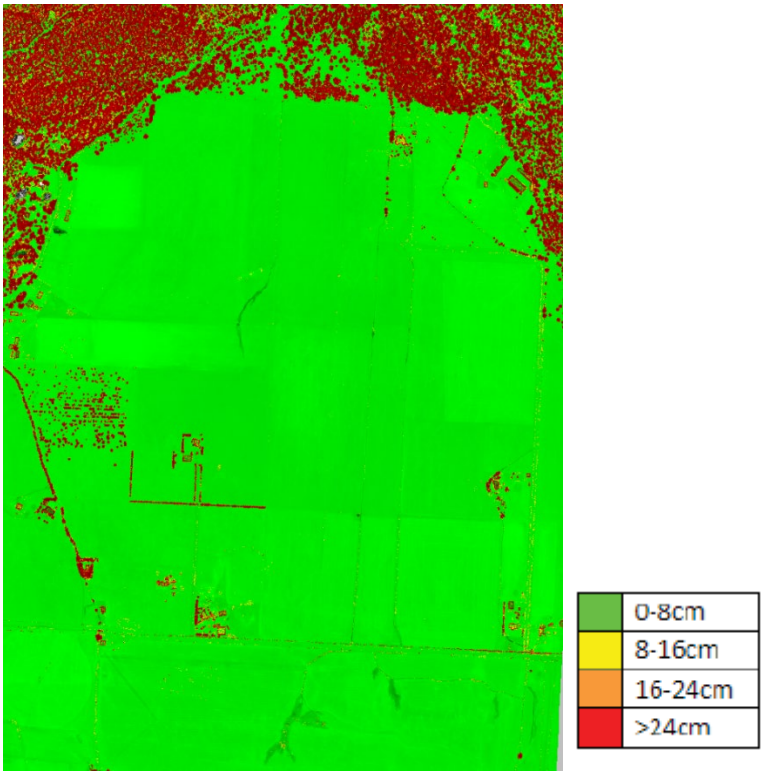
Less than 8-cm: Green

8 to 16-cm: Yellow

16 to 24-cm: Orange

Greater than 24-cm: Red

Figure 4. Swath Separation Image



2.11 Point Density

The acquisition parameters were designed to acquire an average first-return density of 8 points/m2. 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 23.25 points/m2 while the average ground classified density was 19.3 points/m2. The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figures 5 and 6.

Figure 5. First Return Point Density

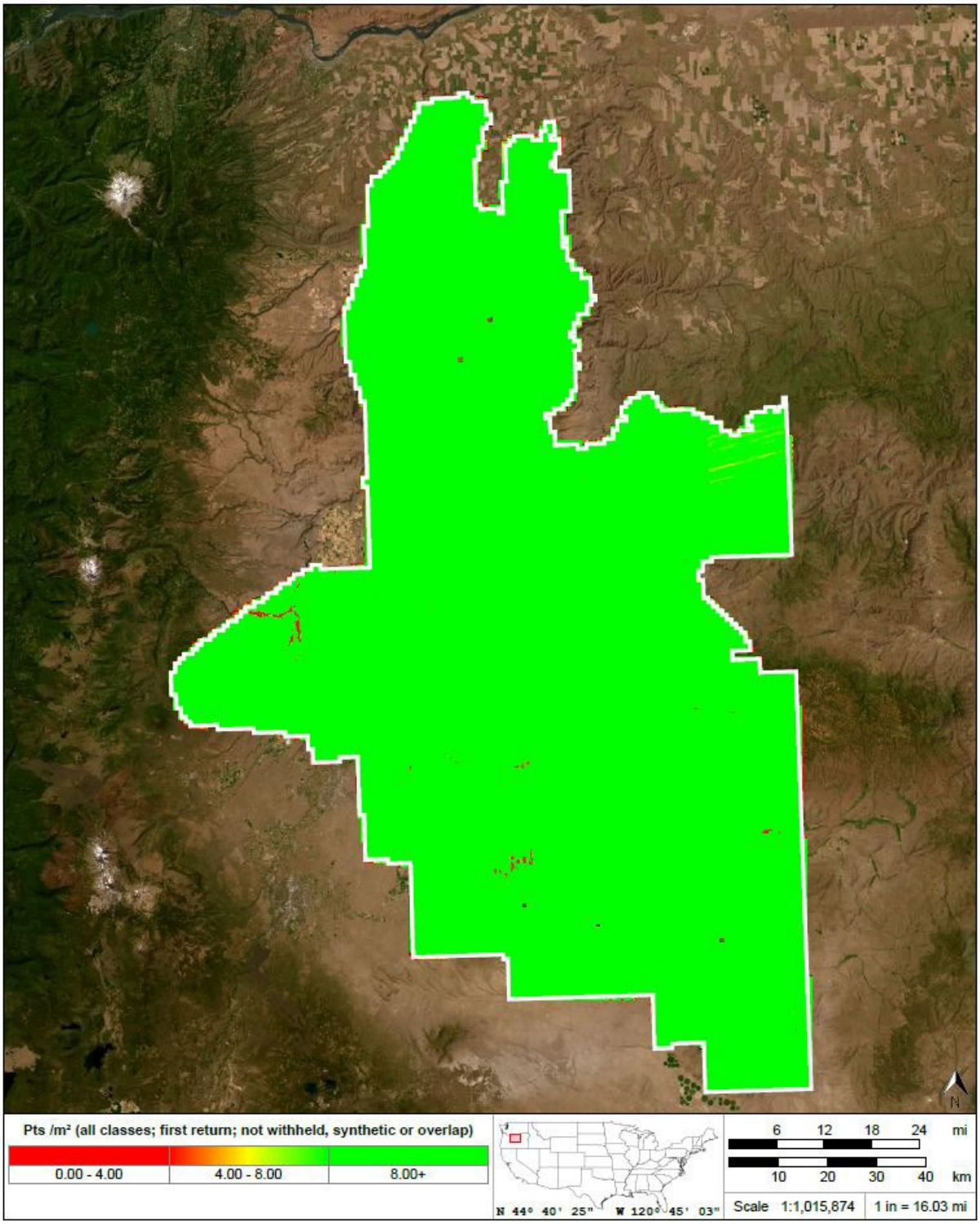
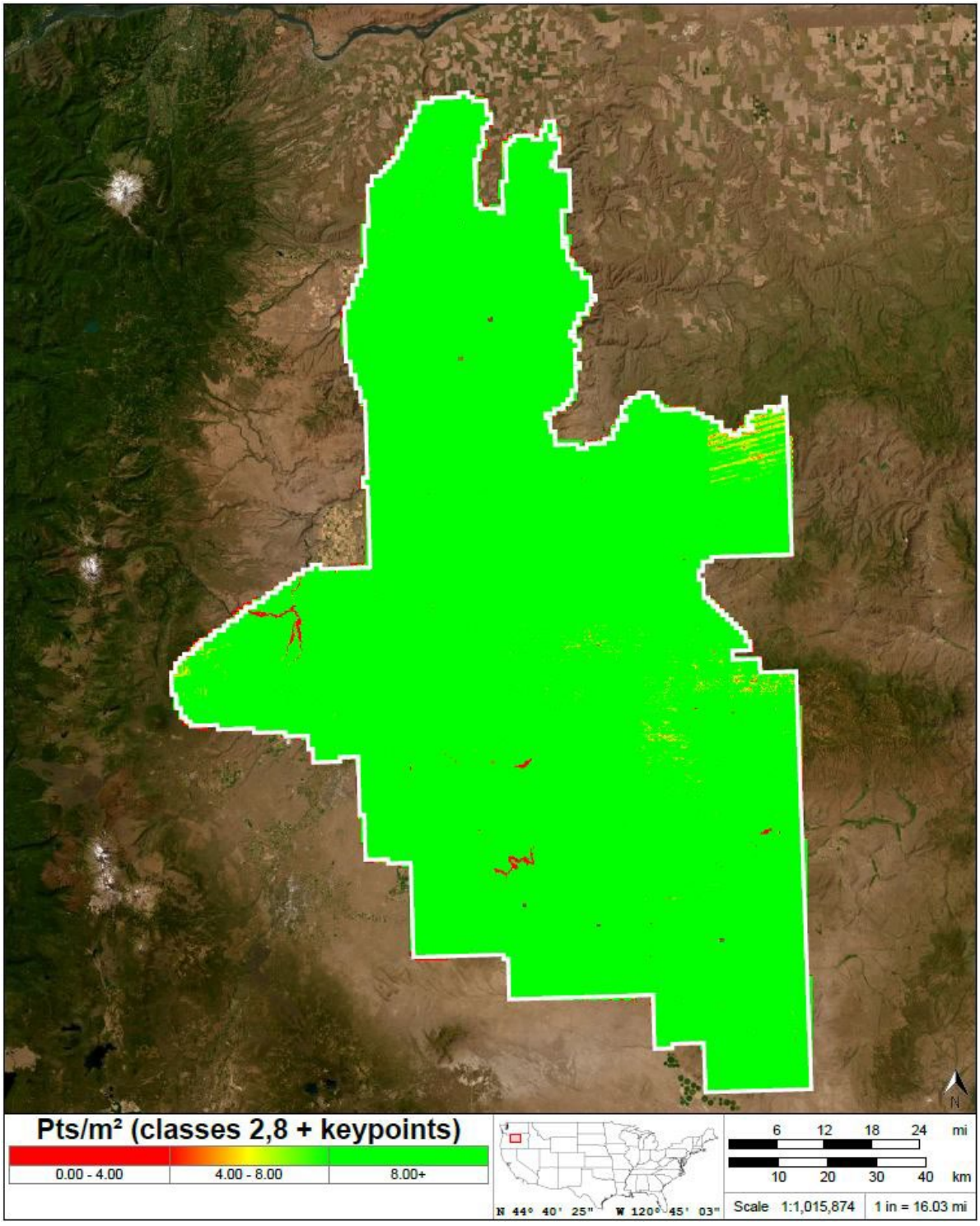


Figure 6. Ground Density



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, and final product development.

2.13 Temporal Exclusion

Temporal Exclusion (Class 22) was used to classify hydro points to different water elevations between flight lines and to classify snow that was present in one flight line and not the other, which precludes us from using snow class because it would cause issues with the surface.

2.14 Software

The below software was used for production of this work unit:

- Proprietary Software
- Applanix + POSPac 8.9
- RiPROCESS 1.9.3.6
- Microstation Connect 10.16.02.34
- GeoCue 2020.1.22.3
- Global Mapper 19.1; 20.1
- TerraModeler 23.013
- TerraScan 23.025
- TerraMatch 23.013
- StripAlign 2.21

3. Accuracy

3.1 Classified Point Cloud

The LAS data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) for a 10-cm RMSEz Vertical Accuracy Class.

3.2 Digital Elevation Model

The Bare-Earth DEM data set was produced to meet ASPRS Positional Accuracy Standard for Digital Geospatial Data (2014) for a 10-cm RMSEz Vertical Accuracy Class.