# WY Yellowstone NP 2020 D20

Lidar Mapping Report
Work Unit WY Yellowstone NP 1RF 2020 - WU225074

November 2022

**Contract #** G16PC00022
**Task Order #** 140G0220F0199

**Contractor** Woolpert
**Project #** 81200

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# 1. Overview

## About

This project contains a comprehensive outline of the 140G0220F0199 WY Yellowstone NP2020 D20 task order issued by the United States Geological Survey's National Geospatial Technical Operations Center (USGS-NGTOC). This task order called for the acquisition and processing of QL2 and QL1 data over two areas of interest covering approximately 6,549 square miles in Yellowstone National Park and Park County, Montana.

This report encompasses the WY_YellowstoneNP_1RF_2020 (WU225074) area of interest (Figure 1-1) and covers 0.2 square miles. This work unit was flown in summer 2022 to collect two small voids caused by vertical cliffs on some of the tallest peaks which were not collected during the initial acquisition and fall within the previously delivered WY_YellowstoneNP_2_2020. The Work Unit. The reflight data was tied into the previously collected data so the sections pertaining to interswath and intraswath accuracy reflect the results from WY_YellowstoneNP_2_2020. There are no hydro features within this work unit which required flattening.

## Purpose

This project will support the 3DEP mission, the Natural Resources Conservation Service (NRCS) high resolution elevation enterprise program and the Federal Emergency Management Agency (FEMA) Risk Mapping Assessment and Planning (MAP) program.

## Specifications

Data for this task order was acquired and produced to meet USGS Lidar Base Specification 2020 revision A standards and the American Society of Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards for Digital Geospatial Data (Edition 1, Version 1.0).

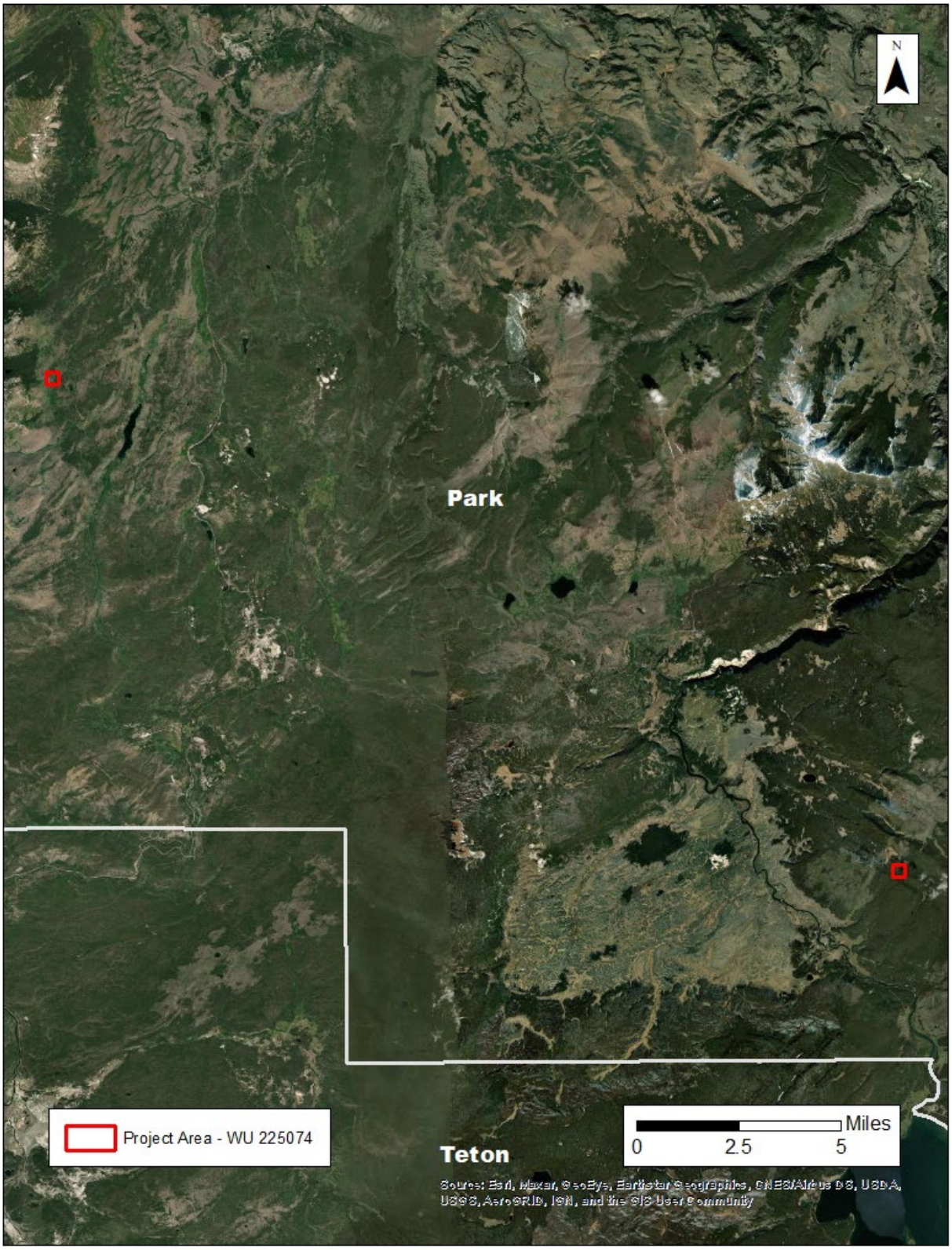
## Spatial Reference

Geospatial data products were produced using the following horizontal and vertical spatial data reference system information listed in Table 1-1.

# Table 1-1. Spatial Reference System

| | | |
|---|---|---|
| **Horizontal** | **EPSG Code** | 6341 |
| | **Datum** | NAD83 (2011) |
| | **Projection** | UTM Zone 12 |
| | **Units** | Meters |
| **Vertical** | **Datum** | NAVD88 |
| | **Geoid** | GEOID18 |
| | **Units** | Meters |
| | **Height Type** | Orthometric |

# Figure 1-1. Project Area - WU225074



# Task Order Deliverables

All data products produced as part of this task order are listed in Table 1-2. All tiled deliverables had a tile size of f 500-meter x 500-meters. Tile names are derived from the US National Grid.

Example: 12TVP920865

This delivery's tiled dataset contains a total of 2 tiles.

## Table 1-2. Deliverables

| **Lidar Data** | |
|---|---|
| Classified lidar point cloud data | Tiles in LAS v1.4 format<br>Classes<br>• 1 – Processed, not Classified<br>• 2 – Ground<br>• 7 – Noise<br>• 9 – Water<br>• 17 – Bridge Decks<br>• 18 – High Noise<br>• 20 – Ignored Ground |
| Intensity imagery | 0.5-meter pixel size, 8-bit gray-scale (linear rescaling from 16-bit intensity) GeoTIFF format |

## Table 1-2: Deliverables (continued)

| | |
|---|---|
| **Vertical Accuracy Data** | |
| Calibration control points | Esri shapefile format delivered with WY_YellowstoneNP_2_2020 |
| NVA and VVA checkpoints | Esri shapefile format delivered with WY_YellowstoneNP_2_2020 |
| Interswath and intraswath test results | Esri shapefile format delivered with WY_YellowstoneNP_2_2020 |
| **Spatial Metadata** | |
| Tile index | Esri shapefile format |
| Swath polygons | Georeferenced, polygonal representation of the detailed extents of each lidar swath<br>Polygon feature class in an Esri file geodatabase |
| Swath separation images | 1-meter pixel size, 8-bit, GeoTIFF format |
| Maximum surface height rasters | 0.5-meter pixel size, 32-bit floating point, GeoTIFF format |
| **Metadata and Reports** | |
| XML metadata | Deliverable-level FGDC CSDGM/USGS MetaParser Compliant metadata in XML format |
| Lidar mapping report | Project report with ancillary data in PDF format |

# 2. Acquisition

## Flight Planning

Acquisition was planned based on the task order specifications listed in Table 2-1.

### Table 2-1. Acquisition Requirements

| Specification | Target |
|---|---|
| Resolution | • 8 points per square meter<br>• 0.35-meter nominal point spacing |
| Overlap | At contractor's discretion, but enough to ensure there are no data gaps between usable portions of the swath and to ensure the aggregate nominal point density (ANPD) is achieved |
| Acquisition Window | During period of annual minimal water level and minimal snow in the fall 2020 leaf-off window running through November 15, 2020 and on July 30 2022 |
| Data Voids | Not allowed except<br>• Where caused by water bodies<br>• Where caused by areas of low near infra-red (NIR) reflectivity (i.e. asphalt or composition roofing)<br>• Where caused by lidar shadowing from buildings or other features<br>• Where appropriately filled-in by another swath |
| Data Acquisition Conditions | Atmospheric<br>• Cloud and fog-free between the aircraft and ground<br>Ground<br>• Snow free<br>• No unusual flooding or inundation, except in cases where the goal of the collection is to map the inundation<br>Vegetation<br>• Leaf-off is preferred<br>Time of Day<br>• Time of day is not of concern |

Flight plans were created using Leica MissionPro software.

## Lidar Sensor Information

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

- Leica TerrainMapper - serial numbers 511, 515, 557

Table 2-2 depicts a summary of sensor information. See Appendix 1 for the sensor calibration reports.

# Table 2-2. Leica Terrain Mapper Sensor Info

| **Sensor Specifications** | |
|---|---|
| Operating Altitude (m AGL) | 300 - 5,500 at 10% reflective target |
| Maximum Measurement Rate (kHz) | 2,000 |
| Scan Angle | 20 - 40 |
| Scan Width | Up to 70% of flight altitude |
| Scan Frequency | Programmable up to 125 Hz (7,500 RPM), 250 scan lines per second |
| Number of Returns | 15 |
| Number of intensity measurements | 15 |
| Pulse Mode(s) | Up to 35 pulses in air |
| **Laser Specifications** | |
| Laser Beam Divergence | 0.25 mrad (1/e) |
| Laser Classification | Class 4 laser product |
| **Accuracy** | |
| Range Resolution | < 1 cm RMS |
| Elevation Accuracy | < 5 cm 1 σ |
| Horizontal Accuracy | < 13 cm 1 σ |
| **Physical Specifications** | |
| Size (cm), Weight (kg)<br>• Scanner<br>• Control Electronics | <br>• 37 W x 68 L x 26 H cm, 47 kg<br>• 45 W x 47 D x 25 H cm, 33 kg |
| Operating Temperature<br>• Scanner<br>• Control Electronics | <br>• 0 - 40°C cabin-side temperature<br>• 0 - 40°C |
| Flight Management | Leica FlightPro |
| Power Consumption | 922 W @ 22.0 – 30.3 VDC |

Source: Leica TerrainMapper Data Sheet
https://leica-geosystems.com/en-US/products/airborne-systems/topographic-lidar-sensors/leica-terrainmapper

# Lidar Sensor Settings

Aerial lidar was acquired using the sensors and settings listed in the Table 2-3.

Table 2-3. Lidar Sensor Settings

| Settings | Blocks 1-4 |
|---|---|
| Max. Number of Returns | 15 |
| Nominal Point Spacing | 0.35 m |
| Nominal Point Density | 8 ppsm |
| Flying Height Above Ground Level | 2,133 m |
| Flight Speed | 150 knots |
| Scan Angle | 40° |
| Scan Rate Used | 1,580 Hz |
| Pulse Rate Used | 150 kHz |
| Multi-Pulse in Air | Enabled |
| Swath Width | 1,553 m |
| Swath Overlap | 25% |

# Timeline

Lidar data was collected from September 29, 2020 through July 30, 2022. A total of 7 individual flight lines were collected. Figure 2-1 shows aerial lidar coverage by lift.

For more information, see the Flight Logs in Appendix 2.

# GNSS and IMU Equipment

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

Flight navigation during acquisition was performed using IGI CCNS (Computer Controlled Navigation System). The pilots are skilled at maintaining their planned trajectory, while holding the aircraft steady and level. If atmospheric conditions are such that the trajectory, ground speed, roll, pitch and/or heading cannot be properly maintained, the mission is aborted until suitable conditions occur.

Base stations were set by acquisition staff and was used to support the aerial data acquisition. Table 2-3 lists the Station ID and coordinates for all base stations operated during acquisition.

For more information, see the GPS/IMU graphics in Appendix 3.

Figure 2-1. Flight Coverage

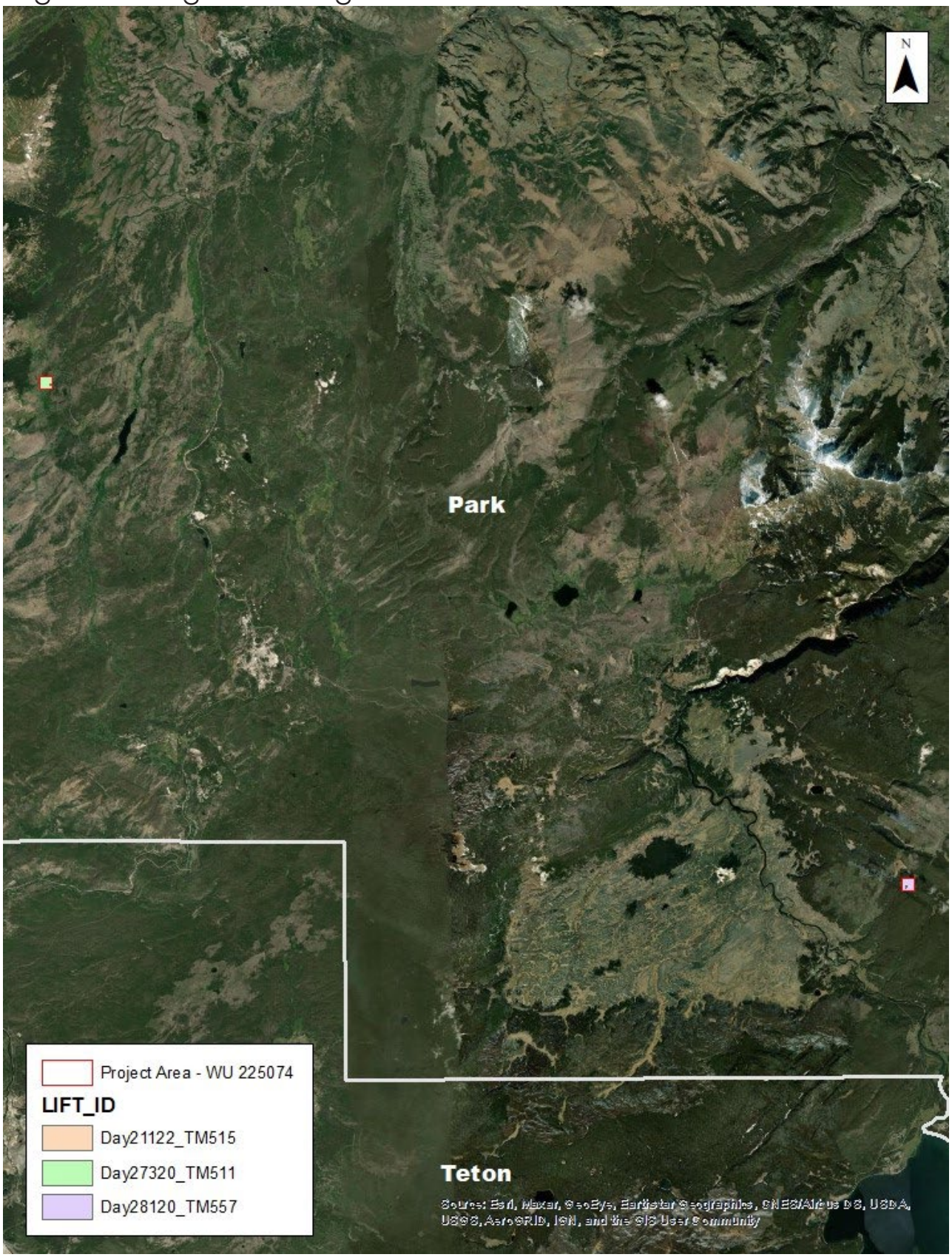


Table 2-4. GNSS Base Stations

| Station Name | Longitude (DMS) | Latitude (DMS) | Ellipsoid Height L1 Phase Center (Meters) |
|---|---|---|---|
| MTSU_CORS | 45° 39' 40.37685" | 111° 2' 42.00897" | 1495.554 |
| IDDR_CORS | 43° 44' 46.00161" | 111° 6' 36.92145" | 1863684 |

# Acquisition Quality Assurance

An initial quality control process was immediately performed on to review the data coverage, airborne GPS data, and trajectory solution.

Woolpert developed a quality assurance and validation plan to ensure the acquired lidar data meets the USGS Base Specification requirements. For quality assurance purposes, the lidar data was processed immediately following acquisition to verify the coverage has appropriate density, distribution, and no unacceptable data voids. Accompanying GPS data was post processed using differential and Kalman filter algorithms to derive a best estimate of trajectory. The quality of the solution was verified to be consistent with the accuracy requirements of the task order. Any required re-flights were scheduled at the earliest opportunity.

The spatial distribution of the geometrically usable first return lidar points was reviewed for density requirements as well as regular and uniform point distribution - verifying the lidar data is spaced so that 90% of the cells in a 2*NPS grid placed over the data contain at least one lidar point. The NPS assessment is made against single swath, first return data located within the geometrically usable center portion (typically ~90%) of each swath. Additionally, the data was reviewed for unacceptable data voids – verifying no area greater than or equal to (4 x ANPS)$^2$ exhibited data coverage gaps.

Woolpert received Notice to Proceed for the project on July 30, 2020 and mobilized to the project area on September 8, 2020. As of September 8, there was both wildfire smoke and snow in the project area. Wildfires continued to burn outside of Yellowstone National Park throughout the month of October, but flight crews were able to adjust mission locations daily to avoid smoke haze.

Significant snowfall September 26-28, 2020 resulted in snow on the north faces of peaks that would persist until 2021. Woolpert continued with acquisition with approval from the USGS to classify snowy peaks as Class 21-Snow. October 24 through October 26, 2020 a strong cold front brought 16+ inches of snow and record cold temperatures. The snow persisted through the rest of the month and effectively ended the fall 2020 acquisition season. The Ground control survey was 100% complete at this time. Data acquisition was 98% complete.

On July 30, 2022 Woolpert collected reflights over small data voids due to vertical cliffs on some of the tallest peaks. This data was processed as delivered in this work unit.

# 3. Processing

## Processing Summary

Once the lidar data passed initial QC, the dataset was corrected for aircraft orientation and movement. This process used airborne inertial, orientation, and GPS data collected during acquisition along with ground-based GPS data. The data went through a geometric calibration that further corrected each laser point. This calibrated data set was used to create the LAS point cloud. The LAS point data was initially classified into “ground” and “non-ground”, then further refined using the classes specified in this task order. Breaklines were drawn to denote hydrological features. After the hydro-flattening process, the final deliverables products were created.

## GPS-IMU Trajectory Processing

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, 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 Appendix 3.

**Software:** POSPac Software v. 5.3, IPAS Pro v.1.35., Novatel Inertial Explorer v8.60.6129

### 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).

### 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 ten (10) centimeters.

### 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.

### PDOP

The PDOP measures the precision of the GPS solution in regard to the geometry of the satellites acquired

and used for the solution.

The 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.

# Geometric Calibration

After the initial phase was complete, a formal reduction process was performed on the data. Laser point position was calculated by associating the SBET position to each laser point return time, scan angle, intensity, etc. Raw laser point cloud data was created for the whole project area in LAS format. Automated line-to-line calibrations were then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Statistical reports were generated for comparison and used to make the necessary adjustments to remove any residual systematic error.

For more information, see the Sensor Calibration Report(s) in Appendix 1.

**Software:** Proprietary Software, TerraMatch v20, Leica CloudPro 1.2.4

# Relative Accuracy: Interswath (Overlap) Consistency

Interswath or overlap consistency was assessed at multiple locations within overlap in non-vegetated areas containing only single returns and located in areas with slopes of less than 10 degrees. To the extent allowed by the data, test areas were chosen where the full width of the overlap was represented. These overlap areas include adjacent, overlapping parallel swaths within a project, cross-tie swaths and a sample of intersecting project swaths in both flight directions, and adjacent, overlapping lifts.

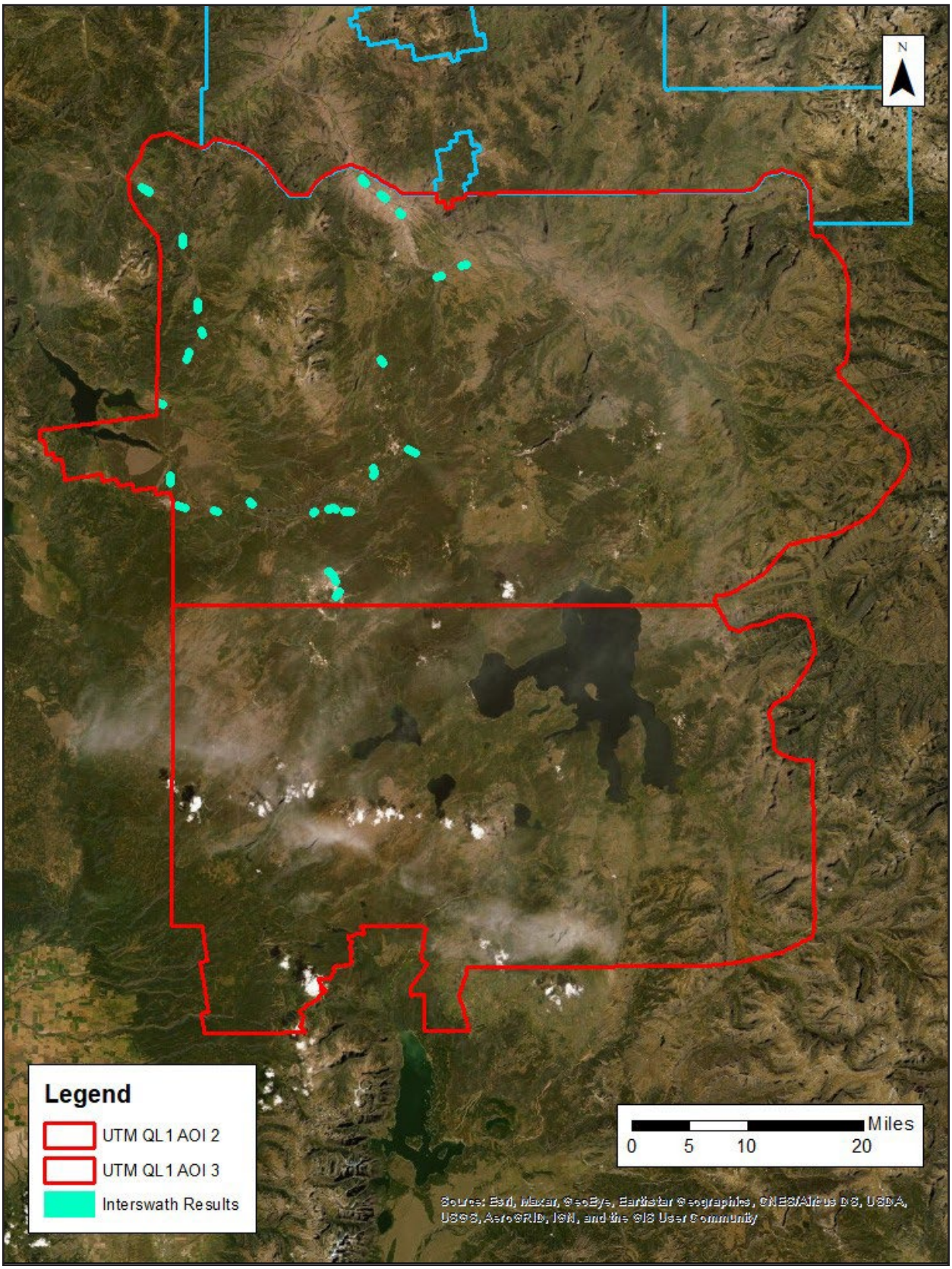
This project required the interswath accuracy to meet ≤ 8 cm RMSDz. Accuracy was assessed in accordance with the USGS Base Specification v2020 revision A.

The interswath consistency results were produced as polygon features in Esri shapefile format. Table 3-1 lists the interswath test results. Figure 3-1 depicts the location of the interswath test locations.

## Table 3-1. Interswath Results

| Minimum (m) | Maximum (m) | RMSDz (m) |
|---|---|---|
| -0.080 | 0.065 | 0.017 |
| -0.035 | 0.060 | 0.019 |
| -0.105 | 0.045 | 0.017 |
| -0.120 | 0.055 | 0.014 |
| -0.070 | 0.080 | 0.019 |
| -0.040 | 0.097 | 0.026 |
| -0.070 | 0.115 | 0.026 |
| -0.077 | 0.060 | 0.021 |
| -0.105 | 0.040 | 0.032 |
| -0.085 | 0.040 | 0.028 |
| -0.030 | 0.150 | 0.017 |
| -0.240 | 0.040 | 0.022 |
| -0.050 | 0.043 | 0.014 |
| -0.090 | 0.030 | 0.018 |
| -0.085 | 0.053 | 0.013 |
| -0.040 | 0.063 | 0.017 |
| -0.046 | 0.010 | 0.019 |
| -0.065 | 0.025 | 0.016 |
| -0.041 | 0.057 | 0.012 |
| -0.110 | 0.067 | 0.023 |
| -0.080 | 0.120 | 0.019 |
| -0.060 | 0.070 | 0.015 |
| -0.080 | 0.075 | 0.022 |
| -0.090 | 0.035 | 0.022 |
| -0.090 | 0.055 | 0.027 |
| -0.080 | 0.045 | 0.025 |

Figure 3-1. Interswath Testing Locations



# Relative Accuracy: Intraswath Precision

Intraswath precision (or 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.

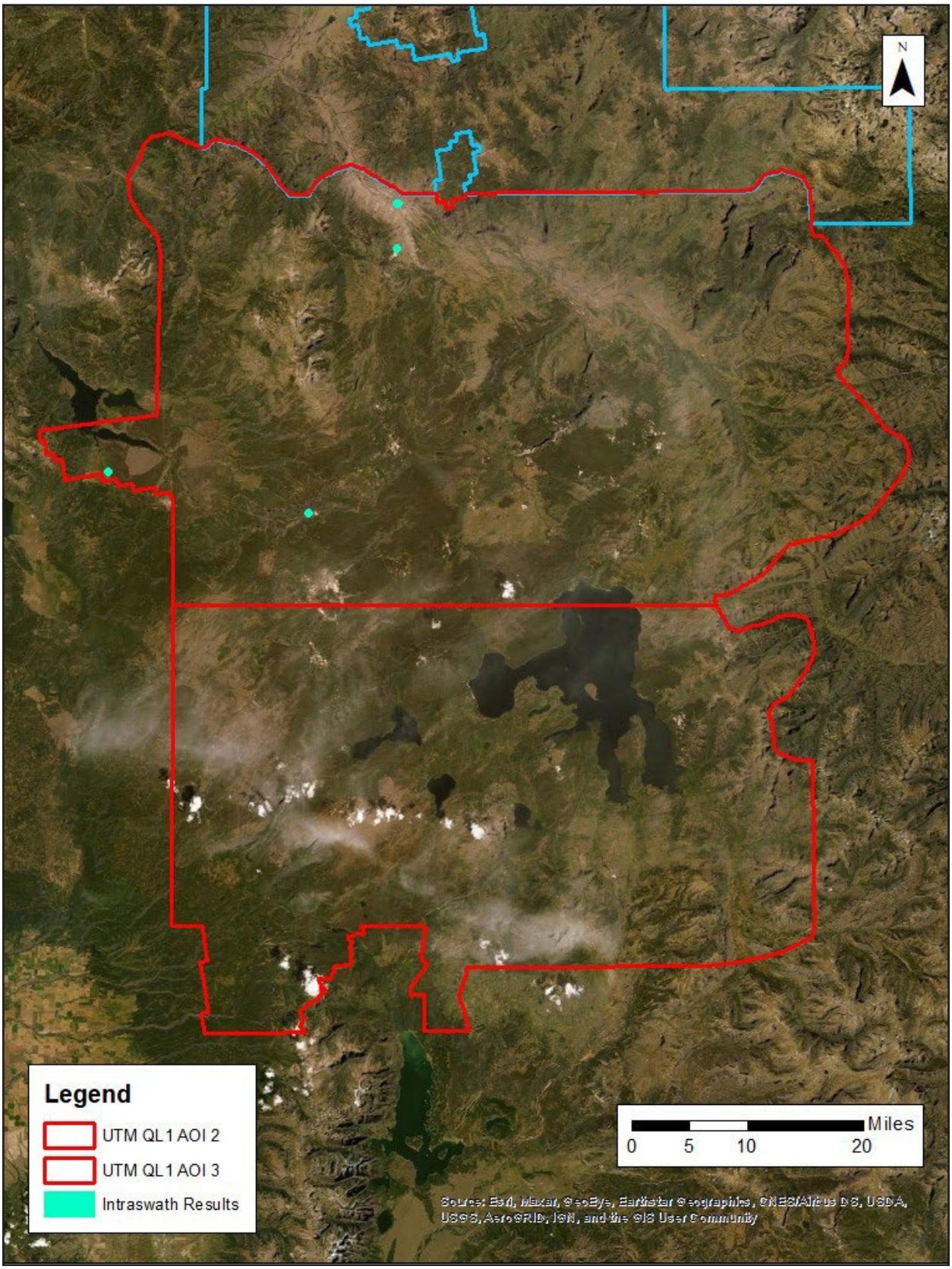
This project required the intraswath accuracy to meet ≤ 6 cm RMSDz. Accuracy was assessed in accordance with the USGS Base Specification v2020 revision A.

The intraswath precision results were produced as polygon features in Esri shapefile format. Table 3-2 lists the intraswath test results. Figure 3-2 depicts the location of the intraswath test locations.

Table 3-2. Intraswath Results

| Minimum (m) | Maximum (m) | RMSDz (m) |
|---|---|---|
| -0.051 | 0.071 | 0.019 |
| -0.073 | 0.025 | 0.030 |
| -0.013 | 0.010 | 0.009 |
| -0.057 | 0.057 | 0.018 |

Figure 3-2. Intraswath Testing Locations



# Lidar Data Classification

LAS data was initially classified as ground and non-ground points “first and only” as well as “last of many” lidar returns. Additional filters were created to meet the task order classification specifications. Statistical absolute accuracy was assessed via direct comparisons of ground classified points to ground RTK survey data. Based on the statistical analysis, the lidar data was then adjusted to reduce the vertical bias when compared to the survey ground control of higher accuracy.

The bare-earth (Class 2 - Ground) lidar points underwent a manual QA/QC step to verify the quality of the DEM as well as a peer-based QC review. This included a review of the DEM surface to remove artifacts and ensure topographic quality. After the bare-earth surface is finalized, it is then used to generate all hydro-breaklines through a semi-automated process.

All ground (Class 2) lidar data inside of the Lake Pond and Double Line Drain hydro flattening breaklines were then classified to water (Class 9) using TerraScan/LP360 macro functionality. A buffer of 0.7 meters was also used around each hydro-flattened feature to classify these ground (Class 2) points to Ignored Ground (Class 20). All Lake Pond Island and Double Line Drain Island features were checked to ensure that the ground (Class 2) points were reclassified to the correct classification after the automated classification was completed.

All overlap data was processed through automated functionality provided by TerraScan to classify the overlapping flight line data to approved classes by USGS. The overlap data was classified using standard LAS overlap bit. These classes were created through automated processes only and were not verified for classification accuracy. Due to software limitations within TerraScan, these classes were used to trip the withheld bit within various software packages. These processes were reviewed and accepted by USGS through numerous conference calls and pilot study areas.

All data was manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler. Global Mapper was used as a final check of the bare earth dataset. GeoCue was then used to create the deliverable industry-standard LAS files. Woolpert proprietary software and LP360 was used to perform final statistical analysis of the classes in the LAS files, on a per tile level to verify final classification metrics and full LAS header information.

Table 3-3 lists the point classifications used.

Table 3-3. Classified Point Breakdown

| Class Number | Class Name |
|---|---|
| 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 |

# Hydrologic Flattening

No Hydro Flattening with this work unit.

# Digital Elevation Model

TerraScan was used to add the hydrologic breakline vertices and export the lattice models. Class 2 (ground) lidar points in conjunction with the hydro breaklines and bridge breaklines were used to create 0.5-meter hydro-flattened bare-earth raster DEM files. Using automated scripting routines within ArcMap, a 32-bit floating point raster GeoTIFF file was created for each tile. Files were clipped to the data extent. Each surface is reviewed using Global Mapper to check for any surface anomalies or incorrect elevations found within the surface.

**Software:** TerraScan v20, GDAL 2.4.0, Esri ArcMap v10.7, Global Mapper v20.0

# Intensity Imagery

Lidar intensity data derived from the acquired lidar data was linearly rescaled from 16-bit intensity and provided as 0.5-meter pixel, 8-bit, 256 gray scale GeoTIFF files. Files were clipped to the data extent.

**Software:** TerraScan v20, Esri ArcMap v10.7

# 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 tile index. A georeferenced, polygonal representation of the detailed extents of each acquired lidar swath was produced as a polygon feature class in an Esri file geodatabase. Swath separation images were produced in GeoTIFF format. Maximum height separation rasters were produced in GeoTIFF format.

# 4. Accuracy Assessment

## Horizontal Accuracy

The data set was produced to meet ASPRS "Positional Accuracy Standards for Digital Geospatial Data" (2014) for a 0.158 cm RMSEx / RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 0.388 cm at a 95% confidence level.

## Classified Lidar Point Cloud Testing

This project required Non-Vegetated Vertical Accuracy (NVA) and Vegetated Vertical Accuracy (VVA) to be tested on the classified lidar point cloud data. The dataset was required to meet a target NVA value of 19.6 cm at a 95% confidence level using an RMSEz target value of 10 cm x 1.9600 and a target VVA value of 30 cm at the 95th percentile. Testing was assessed and reported using guidelines developed by the National Digital Elevation Program (NDEP) and the American Society for Photogrammetry and Remote Sensing (ASPRS).

The NVA and VVA values were calculated using independent checkpoints that were not used in the calibration or post processing of the lidar point cloud data. Checkpoints were distributed throughout the project area. NVA checkpoints were located in bare earth and urban (non-vegetated) land cover classes. VVA checkpoints were located in brush/tall grass/weeds (vegetated) land cover classes. These checkpoints were surveyed using GPS techniques. See the survey report for acquisition methodologies.

Testing was performed using TINs created from the final calibrated and controlled swath data. For each NVA checkpoint, an elevation value was derived from the TIN at the point's x,y location. This value was compared to the checkpoint's surveyed elevation value.

The classified lidar point cloud accuracy test results are listed below in Table 4-1.

Table 4-1. Classified Point Cloud Vertical Accuracy

| | Result | Points Used |
|---|---|---|
| NVA | 0.034 m RMSEz<br>0.067 m at 95% CL | 24 |
| VVA | 0.114 at 95th Percentile | 12 |

## Digital Elevation Model Testing

This project required Non-Vegetated Accuracy (NVA) and Vegetated Vertical Accuracy (VVA) testing of the digital elevation model (DEM) dataset. The calculated NVA value was required to meet 19.6 cm at a 95% confidence level using an RMSEz target value of 10 cm x 1.9600. VVA was required to meet 0.30 cm at the 95th percentile error. Testing was assessed and reported using guidelines developed by the National Digital Elevation Program (NDEP) and the American Society for Photogrammetry and Remote Sensing (ASPRS).

Testing was performed using the bare earth DEM created as part of this task order. For each checkpoint, an elevation value was derived from the DEM at the point's x,y location. This value was compared to the checkpoint's surveyed elevation value.

The NVA and VVA values were calculated using independent checkpoints that were not used in the calibration or post processing of the lidar point cloud data. Checkpoints were distributed throughout the project area. NVA checkpoints were located in bare earth and urban (non-vegetated) land cover classes. VVA checkpoints were located in brush/tall grass/weeds (vegetated) land cover classes. These checkpoints were surveyed using GPS techniques. See the survey report for acquisition methodologies.

The classified lidar point cloud accuracy test results are listed below in Table 4-2.

## Table 4-2. DEM Accuracy

| | Result | Points Used |
|---|---|---|
| NVA | 0.035 m RMSEz<br>0.0686 m at 95% CL | 24 |
| VVA | 0.071 at 95th Percentile | 12 |

# Appendix 1: Sensor Calibration Report

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Leica Geosystems

# Leica Geosystems
## Leica TerrainMapper-LN
## Calibration Certificate

| | |
|---|---|
| **Product** | Leica TerrainMapper-LN |
| **Serial Number** | 91511 |
| **Date** | 03 July 2019 |
| **Inspector** | Mark O'Neal |

**Leica Geosystems AG**
Heinrich-Wild-Strasse
CH-9435 Heerbrugg
Schweiz
**www.leica-geosystems.com**

Document Code: 871495

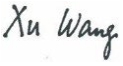
# 1. System Components

| Component | Type | Serial Number |
|---|---|---|
| Pod | TerrainMapper Pod | 91511 |
| GNSS/IMU | Litef LCI-100C 500 Hz | 1139 |
| LiDAR Unit | Hyperion2 LiDAR Unit | 5511 |
| Camera Head | CH82 | 82659 |
| Lens | NAT-D 2.8/80 | 80254 |

# 2. Estimation Process

| | | Passed | Date | Inspector |
|---|---|---|---|---|
| Image Flight | completed | ok | 10.05.2019 | Philip Benz |
| Image Quality Check | checked | ok | 16.05.2019 | Philip Benz |
| Image Calibration | completed | ok | 18.05.2019 | Xu Wang |
| Image Misalignment Update | completed | ok | 02.07.2019 | Mark O'Neal |
| LiDAR Flight | completed | ok | 10.17.2018 | Deniz Arslan |
| LiDAR Quality Check | checked | ok | 23.10.2018 | Rene Heirli |
| LiDAR Calibration and Accuracy | completed | ok | 24.10.2018 | Robert Bosch |
| LiDAR Misalingment Update | completed | | | |

# 3. Inspectors

| | | | |
|---|---|---|---|
| **Name** | Bernhard Riedl | 15.11.2018 |  |
| **Position** | Production Manager | | |
| **Name** | Robert Bosch | 23.05.2019 |  |
| **Position** | Support Engineer | | |
| **Name** | Michael Vetter | 03.07.2019 |  |
| **Position** | Support Engineer | | |

# 4. Remarks

# 5. LiDAR Calibration Results

The calibration results for the LiDAR Unit are only valid for:

- IMU and Pod as listed in the System Components section

## *5.1 LiDAR Geometric Calibration Results*

| **IMU Misalignment** | | **Value** | **Unit** |
|---|---|---|---|
| | ω | -0.138877 | degree |
| | Φ | 0.130994 | degree |
| | κ | -0.006412 | degree |
| **Boresight** | | **Value** | **Unit** |
| | Θ | 0.001052 | degree |
| | Φ | -0.001885 | degree |
| **Receiver 1** | | **Value** | **Unit** |
| Range | Δ Offset | 0.000000 | meters |
| **Wedge 0** | | **Value** | **Unit** |
| Wedge | Δ Alpha | 0.001241 | degree |
| Wedge Position | Δ Offset | -0.426898 | degree |
| Position Correction | X | -0.019523 | degree |
| | Y | 0.007883 | degree |
| Mount | Roll | -0.020901 | degree |
| | Pitch | 0.107683 | degree |
| Rotation Axis | Roll | 0.103712 | degree |
| | Pitch | 0.124140 | degree |
| **Wedge 1** | | **Value** | **Unit** |
| Wedge | Δ Alpha | -0.009545 | degree |
| Wedge Position | Δ Offset | 0.412993 | degree |
| Position Correction | X | 0.004000 | degree |
| | Y | 0.011085 | degree |
| Mount | Roll | 0.102859 | degree |
| | Pitch | 0.025756 | degree |
| | Speed Pitch | 1.50E-06 | degree/rps$^2$ |
| Rotation Axis | Roll | 0.114811 | degree |
| | Pitch | -0.080531 | degree |

**LiDAR Geometric Calibration File**

HYPERION_GEOMETRY_LIDARUNIT-5511-C-855570-DATETIME-20181023-153458.XML

| | | |
|---|---|---|
| | Date | 23.10.2018 |
| **LiDAR Misalingment Flight** | Date | **-** |
| **LiDAR Misalingment Update Completed** | Date | **-** |

## 5.2 LiDAR Unit Accuracy Check

Accuracy checks:

- Deviation of two perpendicular lines to GCP's
- Difference of two perpendicular lines
- Difference of forward and backward scan of one line

### 5.2.1 Multi-line accuracy of two perpendicular lines to ground control points

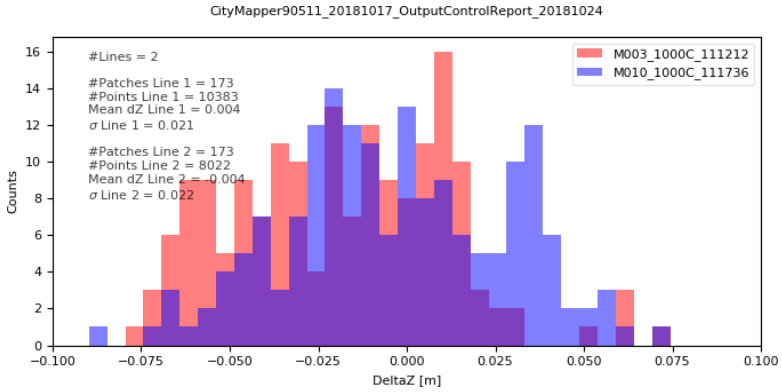



Figure 1 Vertical distance to ground control points at 1000 m AGL.

### 5.2.2 Difference of forward and backward scan of one line

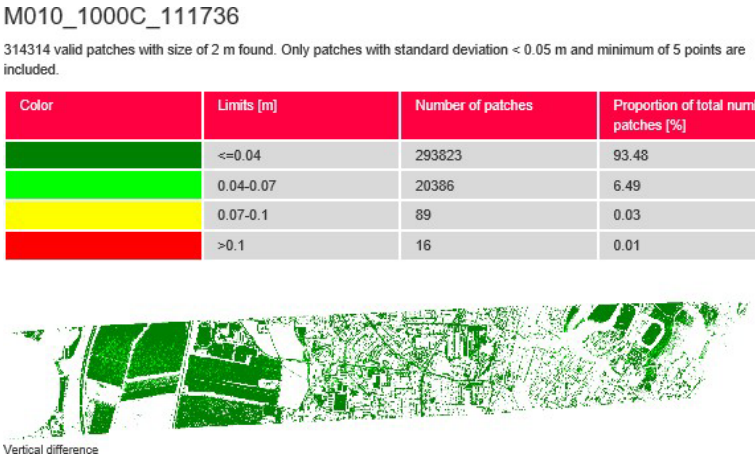



Figure 2 Vertical difference betweeen forward and backward scan at 1000 m AGL.

### 5.2.3 Multi-line accuracy between two perpendicular lines

M003_1000C_111212_vs_M010_1000C_111736

39940 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

| Color | Limits [m] | Number of patches | Proportion of total number of patches [%] |
|---|---|---|---|
| | <=0.04 | 32066 | 80.29 |
| | 0.04-0.07 | 7841 | 19.63 |
| | 0.07-0.1 | 21 | 0.05 |
| | >0.1 | 12 | 0.03 |

Vertical difference

Figure 3 Vertical difference betweeen two perpendicular lines at 1000 m AGL.

# 6. Imaging Sensors Estimation Results

The estimation results for the camera head and lens combination are only valid for:

- IMU and Pod as listed in the System Components section.
- Camera Head, lens and specified position as listed in the Estimation Results sections.

## *6.1 Camera Model of distortion free images*

All factory calibration results contain fixed nominal focal lengths and zero principal point offsets.
Leica HxMap applies the grid to create distortion-free images of nominal focal length and pixel size.

### *6.1.1 CH8x Model*

| | | | **Component** |
|---|---|---|---|
| **Camera Head** | | | CH82 |
| **Lens** | | | NAT-D 2.8/80 |
| **Camera Model** | | | |
| **Focal Length** | | | **Distance** [mm] |
| | c | | 83.00 |
| **Radial Symmetric Distorsion** | | | **Distance** [mm] |
| | $k_0$ | | 0.0000 |
| | $k_1$ | | 0.0000 |
| | $k_2$ | | 0.0000 |
| **Decentering Distortion** | | | **Distance** [mm] |
| | $p_1$ | | 0.0000 |
| | $p_2$ | | 0.0000 |
| **Non-Orthogonality Distortion** | | | **Distance** [mm] |
| | $b_1$ | | 0.0000 |
| | $b_2$ | | 0.0000 |
| **Pixel Size** (Height and Width) | | | **Distance** [mm] |
| | RGB | | 0.0052 |
| | NIR | | 0.0120 |
| **Rows and Columns** | | **Rows** | **Columns** |
| | Active RGB | 7752 | 10320 |
| | Raw RGB | 7788 | 10336 |
| | Active NIR | 3654 | 4478 |
| | Raw NIR | 3366 | 4500 |

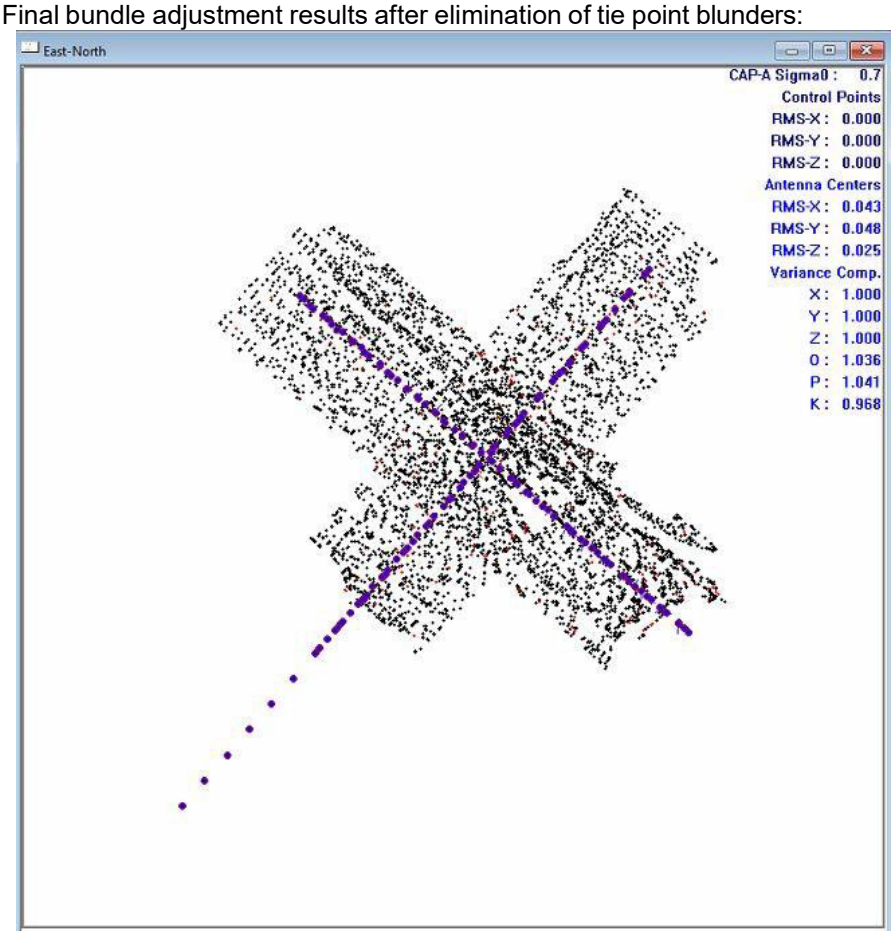
## 6.2 Results of Geometric Calibration

### 6.2.1 Calibration method for Green Reference Band

Estimation of additional parameters (focal length, principal point, radial symmetric distortion, correction grid) and IMU misalignment in simultaneous bundle adjustment

| **Reference band (green)** | **Distance** [mm] |
|---|---|
| Resulting sigma naught of bundle adjustment: | 0.0007 |

Final bundle adjustment results after elimination of tie point blunders:




### 6.2.2 Calibration method for Other Spectral Bands

Estimation of additional parameters (correction grid), based on the result for green in simultaneous bundle adjustment

| **Other Spectral Bands** | **Distance** [mm] |
|---|---|
| Co-registration to green better than: | 0.002 |

Leica HxMap applies the grid to create distortion-free images of nominal focal length and fixed pixel size of 0.0052 mm.

## *6.3 Estimation Results for Nadir Camera Head and Lens*

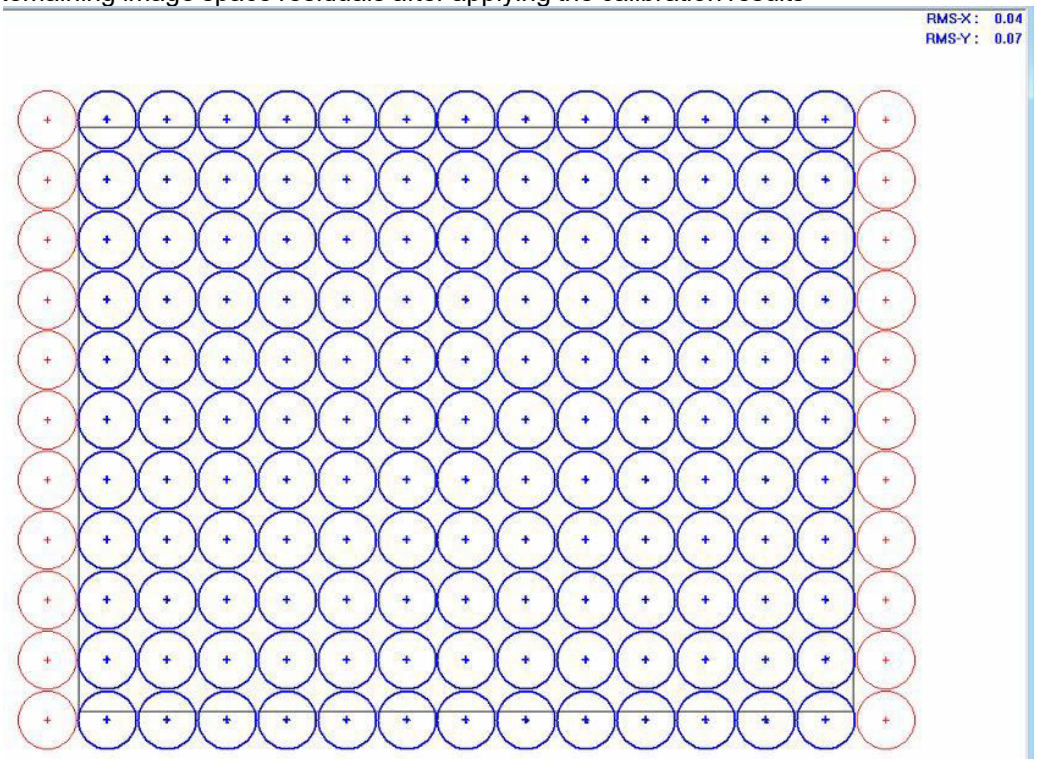
| | | Component | Serial Number |
|---|---|---|---|
| **Camera Head** | | CH82 | 82659 |
| **Lens** | | NAT-D 2.8/80 | 80254 |
| **View Direction in Pod Position** | | Nadir | |
| **IMU Misalignment** | | **Angle** [degree] | |
| | ω | -0.00815 | |
| | Φ | 0.00028 | |
| | κ | -0.26654 | |
| **Principal Point** | | **Distance** [mm] | |
| | x | 0.0000 | |
| | y | 0.0000 | |
| **Focal Length** | | **Distance** [mm] | |
| | c | 83.00 | |

**Geometric Calibration File**

RCD30_Geometry_CameraHead-82659-E-798528_LensSystem-80254-B-785423_DateTime-20190518-214751.xml

| | | |
|---|---|---|
| **Geometric Calibration Date** | Date | 18.05.2019 |
| **Radiometric Calibration Date** | Date | 05.02.2019 |
| **Misalingment Flight** | Date | 23.06.2019 |
| **Misalingment Update Completed** | Date | 02.07.2019 |

Remaining image space residuals after applying the calibration results




Radius of circles is 0.0007 mm

- when it has to be right

Leica Geosystems

# Leica Geosystems
## Leica TerrainMapper-L
## Calibration Certificate

| | |
|---|---|
| **Product** | Leica TerrainMapper-L |
| **Serial Number** | 90515 |
| **Date** | 12 December 2018 |
| **Inspector** | Robert Bosch |

**Leica Geosystems AG**
Heinrich-Wild-Strasse
CH-9435 Heerbrugg
Schweiz
**www.leica-geosystems.com**

Document Code: 871495

# 1. System Components

| Component | Type | Serial Number |
|---|---|---|
| Pod | Terrainmapper Pod | 90515 |
| GNSS/IMU | Litef LCI-100C 500 Hz | 1226 |
| LiDAR Unit | Hyperion2 LiDAR Unit | 5516 |

# 2. Estimation Process

| | | Passed | Date | Inspector |
|---|---|---|---|---|
| LiDAR Flight | completed | ok | 29.11.2018 | Philip Benz |
| LiDAR Quality Check | checked | ok | 06.12.2018 | Rene Heierli |
| LiDAR Calibration and Accuracy | completed | ok | 12.12.2018 | Robert Bosch |
| LiDAR Misalignment Update | completed | | | |

# 3. Inspectors

| | | | |
|---|---|---|---|
| **Name** | Bernhard Riedl | 12.12.2018 |  |
| **Position** | Production Manager | | |
| **Name** | Robert Bosch | 12.12.2018 |  |
| **Position** | Support Engineer | | |

# 4. Remarks

# 5. LiDAR Calibration Results

The calibration results for the LiDAR Unit are only valid for:

- IMU and Pod as listed in the System Components section

## *5.1 LiDAR Geometric Calibration Results*

| **IMU Misalignment** | | **Value** | **Unit** |
|---|---|---|---|
| | ω | -0.022555 | degree |
| | Φ | 0.056357 | degree |
| | κ | 0.000504 | degree |
| **Boresight** | | **Value** | **Unit** |
| | Θ | 0.015419 | degree |
| | Φ | -0.001923 | degree |
| **Receiver 1** | | **Value** | **Unit** |
| Range | Δ Offset | 0.000000 | meters |
| **Wedge 0** | | **Value** | **Unit** |
| Wedge | Δ Alpha | -0.043014 | degree |
| Wedge Position | Δ Offset | 0.442789 | degree |
| Position Correction | X | -0.012826 | degree |
| | Y | 0.000012 | degree |
| Mount | Roll | 0.045379 | degree |
| | Pitch | 0.210132 | degree |
| Rotation Axis | Roll | 0.031087 | degree |
| | Pitch | 0.076675 | degree |
| **Wedge 1** | | **Value** | **Unit** |
| Wedge | Δ Alpha | -0.005517 | degree |
| Wedge Position | Δ Offset | 0.559649 | degree |
| Position Correction | X | 0.030760 | degree |
| | Y | -0.001169 | degree |
| Mount | Roll | 0.012366 | degree |
| | Pitch | 0.054254 | degree |
| | Speed Pitch | 1.50E-06 | degree/rps$^2$ |
| Rotation Axis | Roll | 0.032485 | degree |
| | Pitch | -0.029191 | degree |

**LiDAR Geometric Calibration File**

HYPERION_GEOMETRY_LIDARUNIT-5516-C-855570-DATETIME-20181204-161828.XML

| | | |
|---|---|---|
| | Date | 04.12.2018 |
| **LiDAR Misalignment Flight** | Date | - |
| **LiDAR Misalignment Update Completed** | Date | - |

## 5.2 LiDAR Unit Accuracy Check

Accuracy checks:

- Deviation of two perpendicular lines to GCP's
- Difference of two perpendicular lines
- Difference of forward and backward scan of one line

### 5.2.1 Multi-line accuracy of two perpendicular lines to ground control points

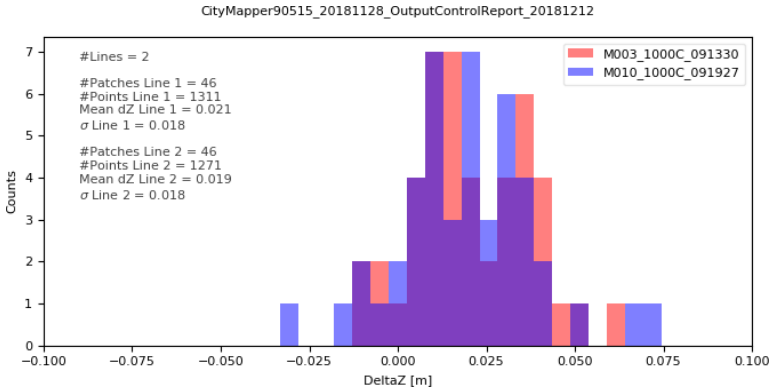



Figure 1 Vertical distance to ground control points at 1000 m AGL.

### 5.2.2 Difference of forward and backward scan of one line

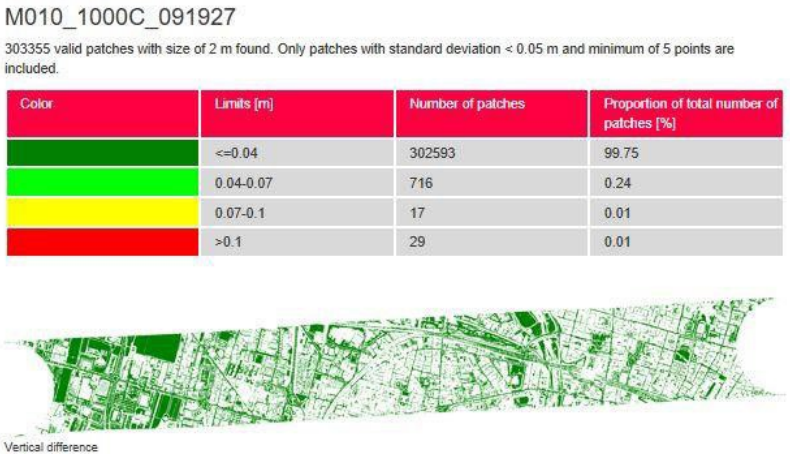



Figure 2 Vertical difference betweeen forward and backward scan at 1000 m AGL.

### *5.2.3 Multi-line accuracy between two perpendicular lines*

M003_1000C_091330_vs_M010_1000C_091927

29588 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

| Color | Limits [m] | Number of patches | Proportion of total number of patches [%] |
|---|---|---|---|
| | <=0.04 | 29546 | 99.86 |
| | 0.04-0.07 | 38 | 0.13 |
| | 0.07-0.1 | 1 | 0.00 |
| | >0.1 | 3 | 0.01 |

Vertical difference

Figure 3 Vertical difference betweeen two perpendicular lines at 1000 m AGL.

- when it has to be right

Leica Geosystems

# Leica Geosystems
## Leica TerrainMapper-LN
## Calibration Certificate

| | |
|---|---|
| **Product** | Leica TerrainMapper-LN |
| **Serial Number** | 91557 |
| **Date** | 01 July 2020 |
| **Inspector** | Ivan Belchev |

**Leica Geosystems AG**
Heinrich-Wild-Strasse
CH-9435 Heerbrugg
Schweiz
**www.leica-geosystems.com**

Document Code: 871495

# 1. System Components

| Component | Type | Serial Number |
|---|---|---|
| Pod | TerrainMapper Pod | 91557 |
| GNSS/IMU | Litef LCI-100C 500 Hz | 1346 |
| LiDAR Unit | Hyperion2 LiDAR Unit | 5561 |
| Camera Head | CH82 | 82673 |
| Lens | NAT-D 2.8/80 | 80264 |

# 2. Estimation Process

| | | Passed | Date | Inspector |
|---|---|---|---|---|
| Image Flight | completed | ok | 23.06.2020 | Deniz Arslan |
| Image Quality Check | checked | ok | 29.06.2020 | Bernhard Riedl |
| Image Calibration | completed | ok | 29.06.2020 | Zoltan Poth |
| Image Misalingment Update | completed | | | |
| LiDAR Flight | completed | ok | 23.06.2020 | Deniz Arslan |
| LiDAR Quality Check | checked | ok | 26.06.2020 | Rene Heierli |
| LiDAR Calibration and Accuracy | completed | ok | 25.06.2020 | Michael Vetter |
| LiDAR Misalingment Update | completed | | | |

# 3. Inspectors

| | | | |
|---|---|---|---|
| **Name** | Bernhard Riedl | 01.07.2020 |  |
| **Position** | Production Manager | | |
| **Name** | Ivan Belchev | 01.07.2020 |  |
| **Position** | Workflow Specialist | | |
| **Name** | Michael Vetter | 01.07.2020 |  |
| **Position** | Support Engineer | | |

# 4. Remarks

# 5. LiDAR Calibration Results

The calibration results for the LiDAR Unit are only valid for:

- IMU and Pod as listed in the System Components section

## *5.1 LiDAR Geometric Calibration Results*

| **IMU Misalignment** | | **Value** | **Unit** |
|---|---|---|---|
| | ω | -0.063987 | degree |
| | Φ | -0.049738 | degree |
| | κ | -0.005305 | degree |
| **Boresight** | | **Value** | **Unit** |
| | Θ | -0.001796 | degree |
| | Φ | -0.003034 | degree |
| **Receiver 1** | | **Value** | **Unit** |
| Range | Δ Offset | 0.000000 | meters |
| **Wedge 0** | | **Value** | **Unit** |
| Wedge | Δ Alpha | -0.045434 | degree |
| Wedge Position | Δ Offset | 0.352942 | degree |
| Position Correction | X | -0.014623 | degree |
| | Y | 0.020330 | degree |
| Mount | Roll | 0.210896 | degree |
| | Pitch | 0.426854 | degree |
| Rotation Axis | Roll | 0.232742 | degree |
| | Pitch | 0.169968 | degree |
| **Wedge 1** | | **Value** | **Unit** |
| Wedge | Δ Alpha | 0.003457 | degree |
| Wedge Position | Δ Offset | 0.393122 | degree |
| Position Correction | X | 0.019198 | degree |
| | Y | -0.002307 | degree |
| Mount | Roll | 0.020583 | degree |
| | Pitch | 0.038667 | degree |
| | Speed Pitch | 1.50E-06 | degree/rps$^2$ |
| Rotation Axis | Roll | 0.061823 | degree |
| | Pitch | 0.034555 | degree |

**LiDAR Geometric Calibration File**

HYPERION_GEOMETRY_LIDARUNIT-5561-D-855570-DATETIME-20200625-085747.XML

| | | |
|---|---|---|
| | Date | 25.06.2020 |
| **LiDAR Misalingment Flight** | Date | **-** |
| **LiDAR Misalingment Update Completed** | Date | **-** |

## 5.2 LiDAR Unit Accuracy Check

Accuracy checks:

- Deviation of two perpendicular lines to GCP's
- Difference of two perpendicular lines
- Difference of forward and backward scan of one line

### 5.2.1 Multi-line accuracy of two perpendicular lines to ground control points

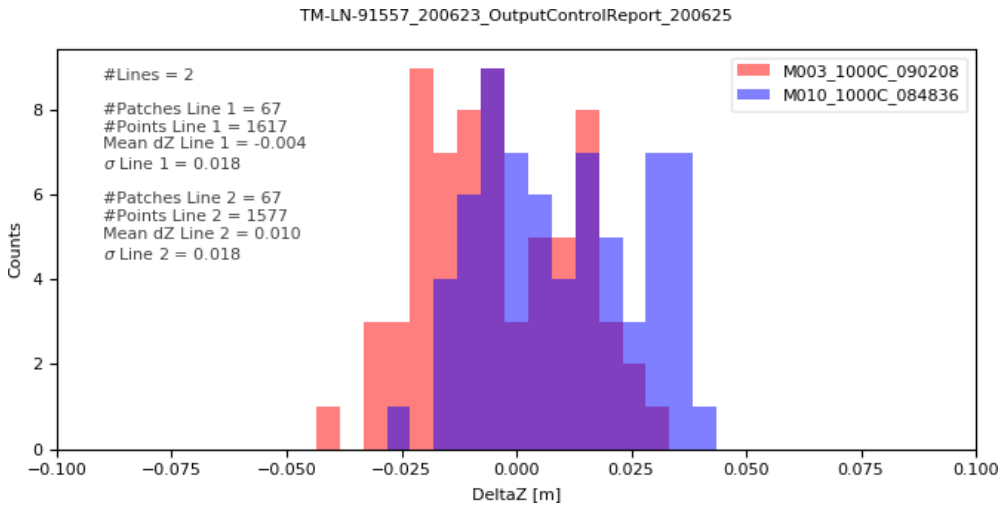



Figure 1 Vertical distance to ground control points at 1000 m AGL.

### 5.2.2 Difference of forward and backward scan of one line

M003_1000C_090208

377750 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

| Color | Limits [m] | Number of patches | Proportion of total number of patches [%] |
|---|---|---|---|
| | <=0.04 | 372019 | 98.48 |
| | 0.04-0.07 | 5529 | 1.46 |
| | 0.07-0.1 | 169 | 0.04 |
| | >0.1 | 33 | 0.01 |

Figure 2 Vertical difference betweeen forward and backward scan at 1000 m AGL.

### *5.2.3 Multi-line accuracy between two perpendicular lines*

M003_1000C_090208_vs_M010_1000C_084836

50693 valid patches with size of 2 m found. Only patches with standard deviation < 0.05 m and minimum of 5 points are included.

| Color | Limits [m] | Number of patches | Proportion of total number of patches [%] |
|---|---|---|---|
| | <=0.04 | 50354 | 99.33 |
| | 0.04-0.07 | 327 | 0.65 |
| | 0.07-0.1 | 6 | 0.01 |
| | >0.1 | 6 | 0.01 |

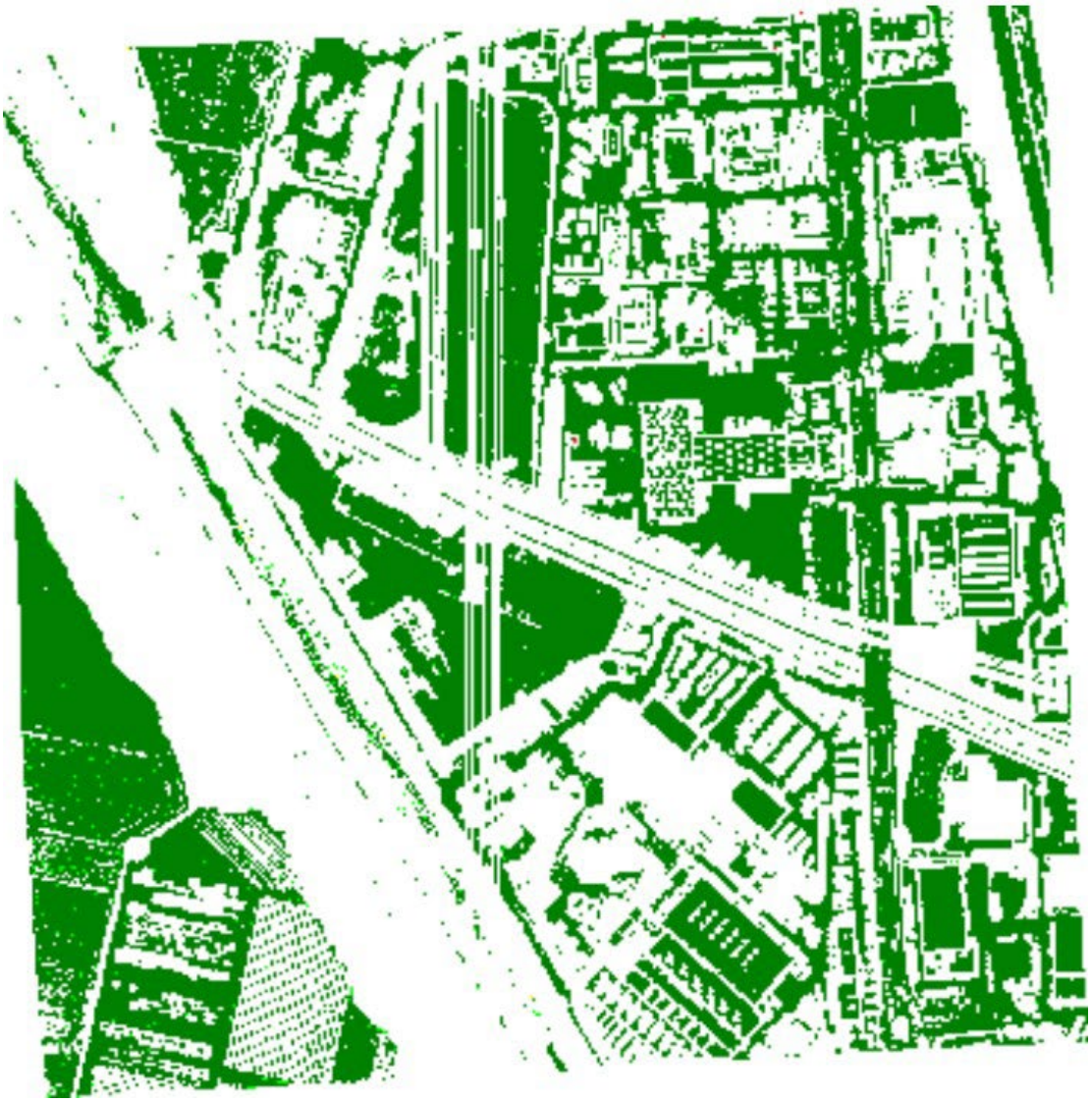


Figure 3 Vertical difference betweeen two perpendicular lines at 1000 m AGL.

# 6. Imaging Sensors Estimation Results

The estimation results for the camera head and lens combination are only valid for:

- IMU and Pod as listed in the System Components section.
- Camera Head, lens and specified position as listed in the Estimation Results sections.

## *6.1 Camera Model of distortion free images*

All factory calibration results contain fixed nominal focal lengths and zero principal point offsets.
Leica HxMap applies the grid to create distortion-free images of nominal focal length and pixel size.

### *6.1.1 CH8x Model*

| | | | **Component** |
|---|---|---|---|
| **Camera Head** | | | CH82 |
| **Lens** | | | NAT-D 2.8/80 |
| **Camera Model** | | | |
| **Focal Length** | | | **Distance** [mm] |
| | c | | 83.00 |
| **Radial Symmetric Distorsion** | | | **Distance** [mm] |
| | $k_0$ | | 0.0000 |
| | $k_1$ | | 0.0000 |
| | $k_2$ | | 0.0000 |
| **Decentering Distortion** | | | **Distance** [mm] |
| | $p_1$ | | 0.0000 |
| | $p_2$ | | 0.0000 |
| **Non-Orthogonality Distortion** | | | **Distance** [mm] |
| | $b_1$ | | 0.0000 |
| | $b_2$ | | 0.0000 |
| **Pixel Size** (Height and Width) | | | **Distance** [mm] |
| | RGB | | 0.0052 |
| | NIR | | 0.0120 |
| **Rows and Columns** | | **Rows** | **Columns** |
| | Active RGB | 7752 | 10320 |
| | Raw RGB | 7788 | 10336 |
| | Active NIR | 3654 | 4478 |
| | Raw NIR | 3366 | 4500 |

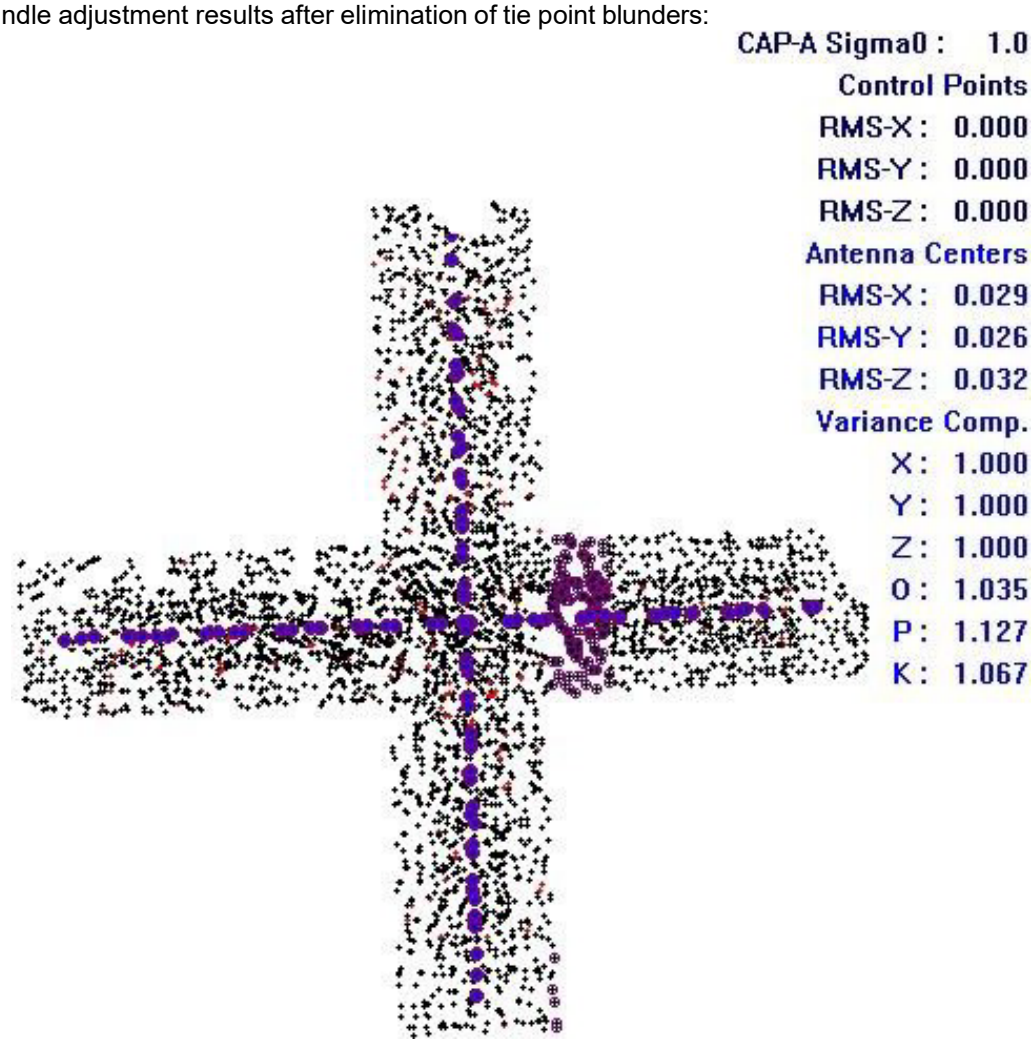
## 6.2 Results of Geometric Calibration

### 6.2.1 Calibration method for Green Reference Band

Estimation of additional parameters (focal length, principal point, radial symmetric distortion, correction grid) and IMU misalignment in simultaneous bundle adjustment

| **Reference band (green)** | **Distance** [mm] |
|---|---|
| Resulting sigma naught of bundle adjustment: | 0.0010 |

Final bundle adjustment results after elimination of tie point blunders:




### 6.2.2 Calibration method for Other Spectral Bands

Estimation of additional parameters (correction grid), based on the result for green in simultaneous bundle adjustment

| **Other Spectral Bands** | **Distance** [mm] |
|---|---|
| Co-registration to green better than: | 0.002 |

Leica HxMap applies the grid to create distortion-free images of nominal focal length and fixed pixel size of 0.0052 mm.

## *6.3 Estimation Results for Nadir Camera Head and Lens*

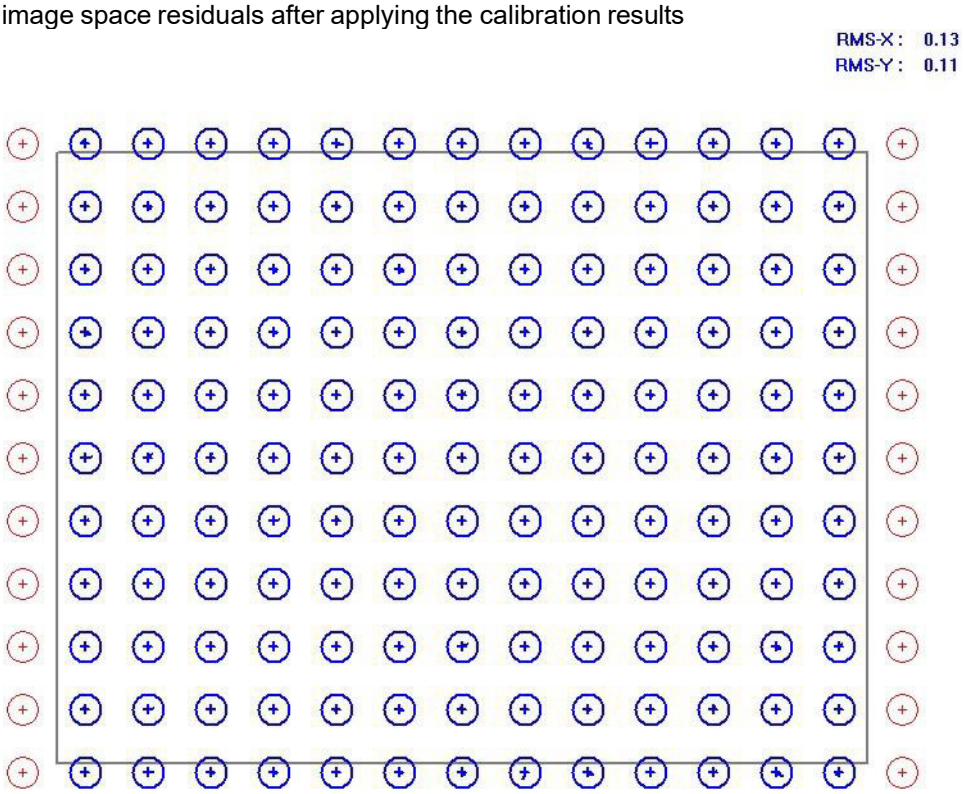
| | | Component | Serial Number |
|---|---|---|---|
| **Camera Head** | | CH82 | 82673 |
| **Lens** | | NAT-D 2.8/80 | 80264 |
| **View Direction in Pod Position** | | Nadir | |
| **IMU Misalignment** | | **Angle** [degree] | |
| | ω | 0.03017 | |
| | Φ | -0.01221 | |
| | κ | -0.25213 | |
| **Principal Point** | | **Distance** [mm] | |
| | x | 0.0000 | |
| | y | 0.0000 | |
| **Focal Length** | | **Distance** [mm] | |
| | c | 83.00 | |

**Geometric Calibration File**

RCD30_Geometry_CameraHead-82673---798528_LensSystem-80264-B-785423_DateTime-20200629-142416.xml

| | | |
|---|---|---|
| **Geometric Calibration Date** | Date | 29.06.2020 |
| **Radiometric Calibration Date** | Date | 30.01.2020 |
| **Misalingment Flight** | Date | - |
| **Misalingment Update Completed** | Date | - |

Remaining image space residuals after applying the calibration results




Radius of circles is 0.0010 mm

# Appendix 2: Flight Logs

# Woolpert Lidar Acquisition Log

| Project Info | | | Date | | |
|---|---|---|---|---|---|
| **Project #** | **Project Name** | **Unique ID** | **Flight Date (UTC)** | **Day of Year** | **Flight #** |
| 81200 | Yellowstone Block 1 | Day273_90511_A | 09/29/2020 | 273 | A |

| Crew | Equipment | Time | | | Airports |
|---|---|---|---|---|---|
| **Pilot** | **Aircraft Make / Model / Tail #** | **Hobbs Start** | **Local Start** | **UTC Start** | **Departing** |
| Marika | Cessna 404 Titan - N404CP | 8049.8 | 09:25:00 | 15:25:00 | KBZN |
| **Operator** | **Sensor Make / Model / Serial #** | **Hobbs End** | **Local End** | **UTC End** | **Arriving** |
| Ryan | Leica Terrain Mapper - 90511 | 8055.9 | 14:29:00 | 20:29:00 | KBZN |

**Conditions**

| Wind Dir (°) | Wind Speed (kts) | Visibility (mi) | Ceiling (ft) | Cloud Cover | Temp. (°C) | Dew Point (°C) | Pressure ("Hg) |
|---|---|---|---|---|---|---|---|
| 200 | 3 | 10 | | Clear | 3 | -1 | 3035 |

| Air Speed (kts) | Altitude AGL (ft) | Altitude MSL (ft) | Airfield Elevation (ft) |
|---|---|---|---|
| 150 | | 13,707 | 4,473 |

**Settings**

| Point Spacing (m) | Point Density (ppsm) | Scan Angle/FOV (°) | Scan Frequency (Hz) | Pulse Rate (kHz) | Laser Power (%) |
|---|---|---|---|---|---|
| 0.35 | 2 | 40 | 150 | 1580 | 100 |

**Verify S-Turns Before Mission**: Yes

| Line # | Direction | Start Time (UTC) | End Time (UTC) | Time On-Line | Satellite | PDOP | Line Notes/Comments |
|---|---|---|---|---|---|---|---|
| 95 | S | 15:25:00 | 15:28:00 | 00:03:00 | 24 | 1.1 | |
| 97 | S | 15:45:00 | 15:49:00 | 00:04:00 | 21 | 1.4 | |
| 96 | N | 15:52:00 | 15:55:00 | 00:03:00 | 20 | 1.5 | |
| 94 | S | 15:57:00 | 16:00:00 | 00:03:00 | 20 | 1.2 | |
| 93 | N | 16:03:00 | 16:06:00 | 00:03:00 | 20 | 1.2 | |
| 92 | S | 16:09:00 | 16:11:00 | 00:02:00 | 21 | 1.2 | |
| 91 | N | 16:15:00 | 16:18:00 | 00:03:00 | 20 | 1.2 | |
| 90 | S | 16:20:00 | 16:23:00 | 00:03:00 | 20 | 1.2 | |
| 89 | N | 16:25:00 | 16:28:00 | 00:03:00 | 19 | 1.3 | |
| 88 | S | 16:31:00 | 16:33:00 | 00:02:00 | 19 | 1.3 | |
| 87 | N | 16:36:00 | 16:38:00 | 00:02:00 | 19 | 1.4 | |
| 86 | S | 16:41:00 | 16:43:00 | 00:02:00 | 18 | 1.4 | |
| 85 | N | 16:46:00 | 16:48:00 | 00:02:00 | 18 | 1.4 | |
| 84 | S | 16:50:00 | 16:53:00 | 00:03:00 | 18 | 1.4 | |
| 83 | N | 16:55:00 | 16:58:00 | 00:03:00 | 18 | 1.3 | |
| 82 | S | 17:00:00 | 17:02:00 | 00:02:00 | 18 | 1.3 | |
| 81 | N | 17:06:00 | 17:07:00 | 00:01:00 | 18 | 1.3 | |
| 80 | S | 17:10:00 | 17:11:00 | 00:01:00 | 20 | 1.2 | |
| 79 | N | 17:14:00 | 17:16:00 | 00:02:00 | 21 | 1.2 | |
| 30 | N | 17:27:00 | 17:41:00 | 00:14:00 | 22 | 1 | |
| 31 | S | 17:44:00 | 17:57:00 | 00:13:00 | 17 | 1.4 | |
| 45 | N | 18:03:00 | 18:17:00 | 00:14:00 | 17 | 1.3 | some snow in the high peaks |
| 46 | S | 18:22:00 | 18:35:00 | 00:13:00 | 19 | 1.2 | some snow in the high peaks |
| 47 | N | 18:38:00 | 18:51:00 | 00:13:00 | 22 | 1 | |
| 48 | S | 18:54:00 | 19:07:00 | 00:13:00 | 22 | 1 | |



**Verify S-Turns After Mission**: Yes

**Additional Comments**

Altitude varies between lines

# Woolpert Lidar Acquisition Log

| Project Info | | | Date | | |
|---|---|---|---|---|---|
| **Project #** | **Project Name** | **Unique ID** | **Flight Date (UTC)** | **Day of Year** | **Flight #** |
| 81200 | Yellowstone NP BLOCKS 1&2 | Day281_91557_1 | 10/07/2020 | 281 | 1 |

| Crew | Equipment | Time | | | Airports |
|---|---|---|---|---|---|
| **Pilot** | **Aircraft Make / Model / Tail #** | **Hobbs Start** | **Local Start** | **UTC Start** | **Departing** |
| Dar Perl | Reims F406 - N406SD | 513.4 | 09:15:00 | 15:14:00 | KBZN |
| **Operator** | **Sensor Make / Model / Serial #** | **Hobbs End** | **Local End** | **UTC End** | **Arriving** |
| Fanning | Leica Terrain Mapper - 91557 | 519 | 13:14:00 | 19:14:00 | KBZN |

**Conditions**

| Wind Dir (°) | Wind Speed (kts) | Visibility (mi) | Ceiling (ft) | Cloud Cover | Temp. (°C) | Dew Point (°C) | Pressure ("Hg) |
|---|---|---|---|---|---|---|---|
| 170 | 3 | 10 | 18,000 | Clear | 4 | 1 | 30.15 |

| Air Speed (kts) | Altitude AGL (ft) | Altitude MSL (ft) | Airfield Elevation (ft) |
|---|---|---|---|
| 150 | 6,998 | 13,665 | 4,471 |

**Settings**

| Point Spacing (m) | Point Density (ppsm) | Scan Angle/FOV (°) | Scan Frequency (Hz) | Pulse Rate (kHz) | Laser Power (%) |
|---|---|---|---|---|---|
| 0.35 | 8 | 40 | 150 | 1580 | 100 |

| | |
|---|---|
| **Verify S-Turns Before Mission** | Yes |

| Line # | Direction | Start Time (UTC) | End Time (UTC) | Time On-Line | Satellite | PDOP | Line Notes/Comments |
|---|---|---|---|---|---|---|---|
| 6 | S | 15:14:00 | 15:17:00 | 00:03:00 | 21 | 1.4 | BLOCK1 (BLOCK 1 COMPLETE)(13665' MSL) |
| | | | | | | | |
| 19 | S | 15:30:00 | 15:42:00 | 00:12:00 | 23 | 1.2 | BLOCK 2 (12,858' MSL) |
| 27 | N | 15:47:00 | 16:00:00 | 00:13:00 | 23 | 1.1 | VARIABLE MSL FOR BLOCKS 1&2 |
| 28 | S | 16:03:00 | 16:16:00 | 00:13:00 | 21 | 1.3 | |
| 29 | N | 16:19:00 | 16:31:00 | 00:12:00 | 20 | 1.2 | |
| 30 | S | 16:34:00 | 16:47:00 | 00:13:00 | 19 | 1.3 | |
| 31 | N | 16:55:00 | 17:08:00 | 00:13:00 | 21 | 1 | |
| 32 | S | 17:12:00 | 17:25:00 | 00:13:00 | 15 | 1.4 | |
| 33 | N | 17:28:00 | 17:41:00 | 00:13:00 | 16 | 1.3 | |
| 34 | S | 17:44:00 | 17:57:00 | 00:13:00 | 16 | 1.2 | |
| 35 | N | 18:00:00 | 18:13:00 | 00:13:00 | 18 | 1 | |
| 36 | S | 18:15:00 | 18:28:00 | 00:13:00 | 20 | 1 | |
| 37 | N | 18:31:00 | 18:43:00 | 00:12:00 | 18 | 1.1 | |
| 38 | S | 18:46:00 | 18:58:00 | 00:12:00 | 18 | 1.2 | |
| 39 | N | 19:01:00 | 19:14:00 | 00:13:00 | 18 | 1.3 | |
| | | | | | | | |
| | | | | | | | 19:20 SCOUTED PARK CO BLOCK 4 |
| | | | | | | | REFLIGHT LINES. SEASONAL SNOW |
| | | | | | | | REMAINS. |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |



| | |
|---|---|
| **Verify S-Turns After Mission** | Yes |

**Additional Comments**

3889 GB WU: 08:52MST WD: 14:04MST MAINT HOBBS: 5460.3

# Woolpert Lidar Acquisition Log

| Project Info | | | Date | | |
|---|---|---|---|---|---|
| **Project #** | **Project Name** | **Unique ID** | **Flight Date (UTC)** | **Day of Year** | **Flight #** |
| 81200 | Yellowstone Voids 2022 | Day211_90515_1 | 07/30/2022 | 211 | 1 |

| Crew | Equipment | Time | | | Airports |
|---|---|---|---|---|---|
| **Pilot** | **Aircraft Make / Model / Tail #** | **Hobbs Start** | **Local Start** | **UTC Start** | **Departing** |
| Comer | Reims F406 - N406WT | 2447 | 10:17:00 | 16:17:00 | KIDA |
| **Operator** | **Sensor Make / Model / Serial #** | **Hobbs End** | **Local End** | **UTC End** | **Arriving** |
| Fanning | Leica Terrain Mapper - 90515 | 2451.1 | 10:26:00 | 16:26:00 | KIDA |

**Conditions**

| Wind Dir (°) | Wind Speed (kts) | Visibility (mi) | Ceiling (ft) | Cloud Cover | Temp. (°C) | Dew Point (°C) | Pressure ("Hg) |
|---|---|---|---|---|---|---|---|
| 350 | 4 | 10 | 17,500 | Clear | 18 | 13 | 30.17 |

| Ground Speed (kts) | Altitude AGL (ft) | Altitude MSL (ft) | Airfield Elevation (ft) |
|---|---|---|---|
| 150 | 5,607 | 14,882 | 4,744 |

**Settings**

| Point Spacing (m) | Point Density (ppsm) | Scan Angle/FOV (°) | Scan Frequency (Hz) | Pulse Rate (kHz) | Laser Power (%) |
|---|---|---|---|---|---|
| | 8 | 40 | 150 | 1645 | 100 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | **Verify S-Turns Before Mission** | Yes |
| **Line #** | **Direction** | **Start Time (UTC)** | **End Time (UTC)** | **Time On-Line** | **Satellite** | **PDOP** | **Line Notes/Comments** | |
| 1 | NE | 16:17:00 | 16:17:00 | 00:01:00 | 19 | 1.1 | | |
| 2 | S | 16:25:00 | 16:26:00 | 00:01:00 | 19 | 1.1 | **6335'AGL; 15,210'MSL** | |



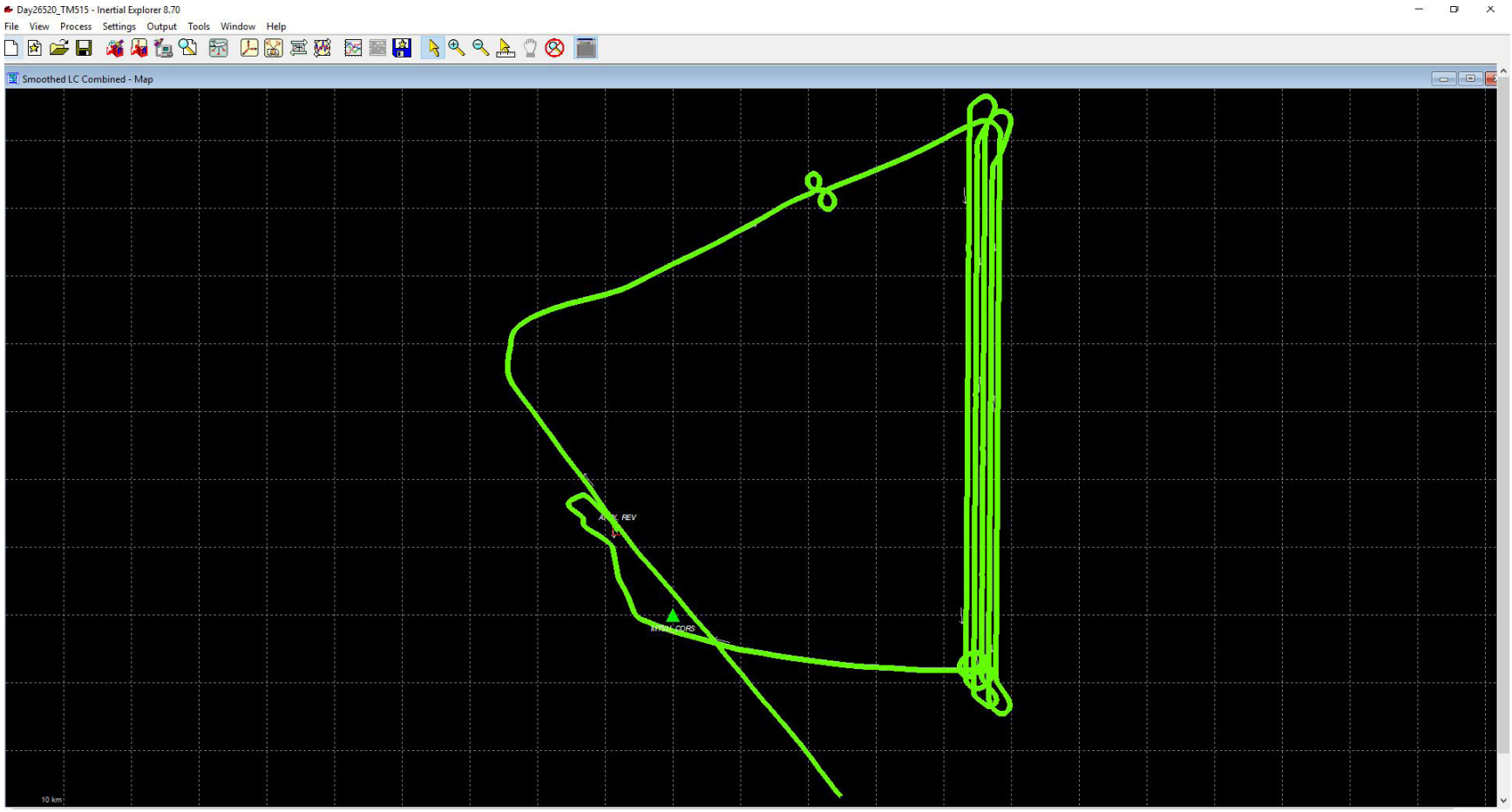
**Verify S-Turns After Mission** Yes

**Additional Comments**

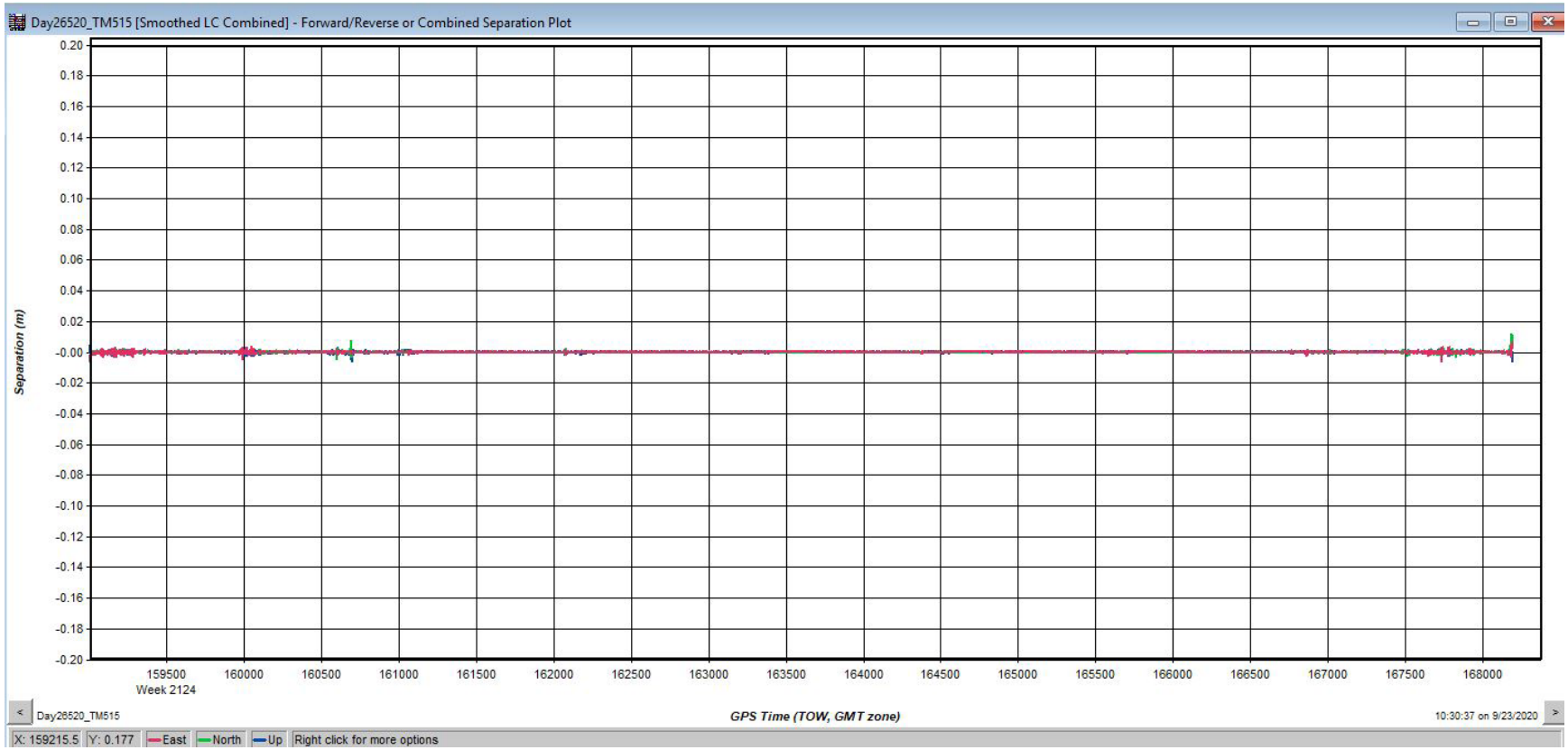
**5106GB WU: 09:42MDT WD: 12:45MDT Mx Hobbs out:6798.5; Mx Hobbs in: 6801.6; Cycles: 7432**

# Appendix 3: GPS / IMU Graphics

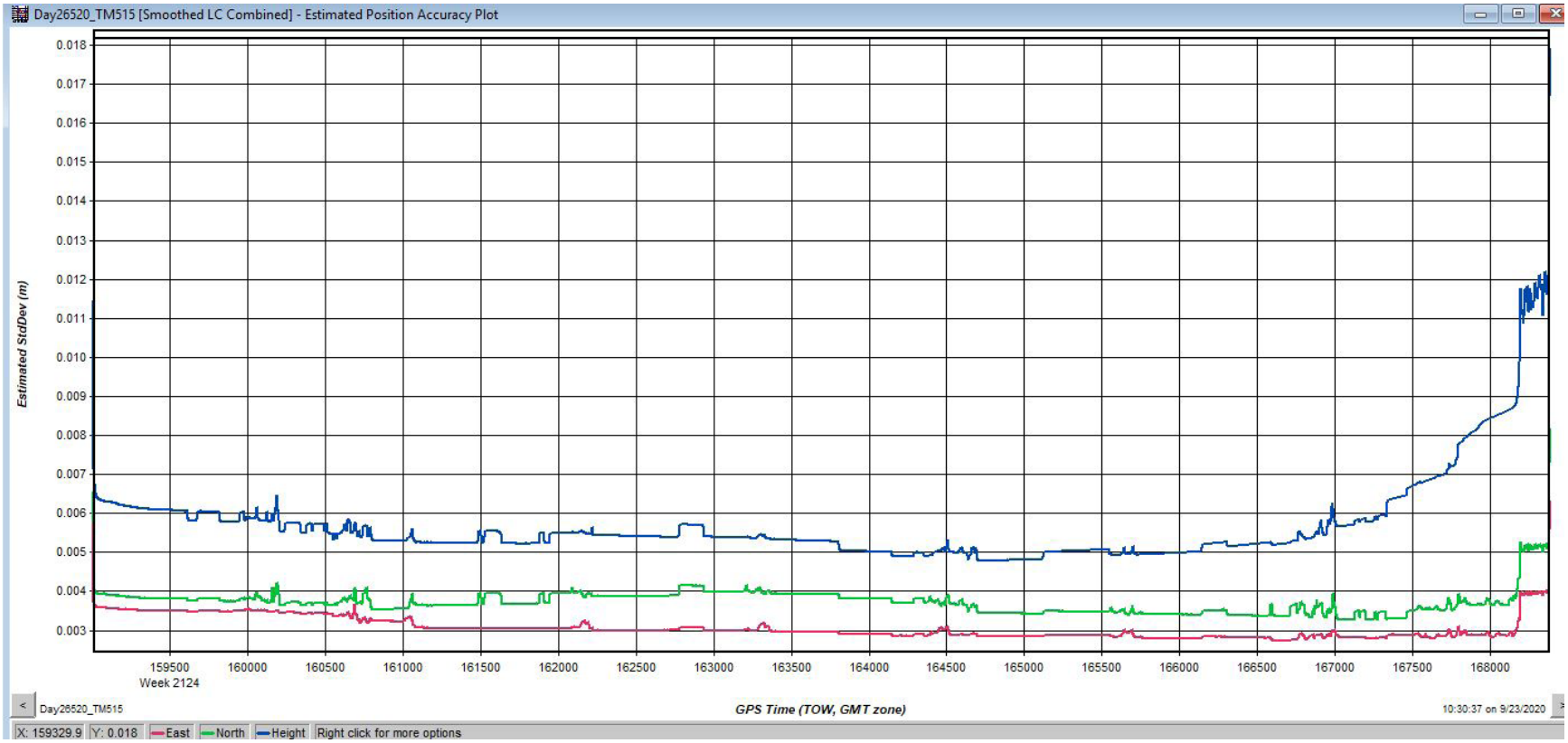
# Day27320_TM511
Trajectory



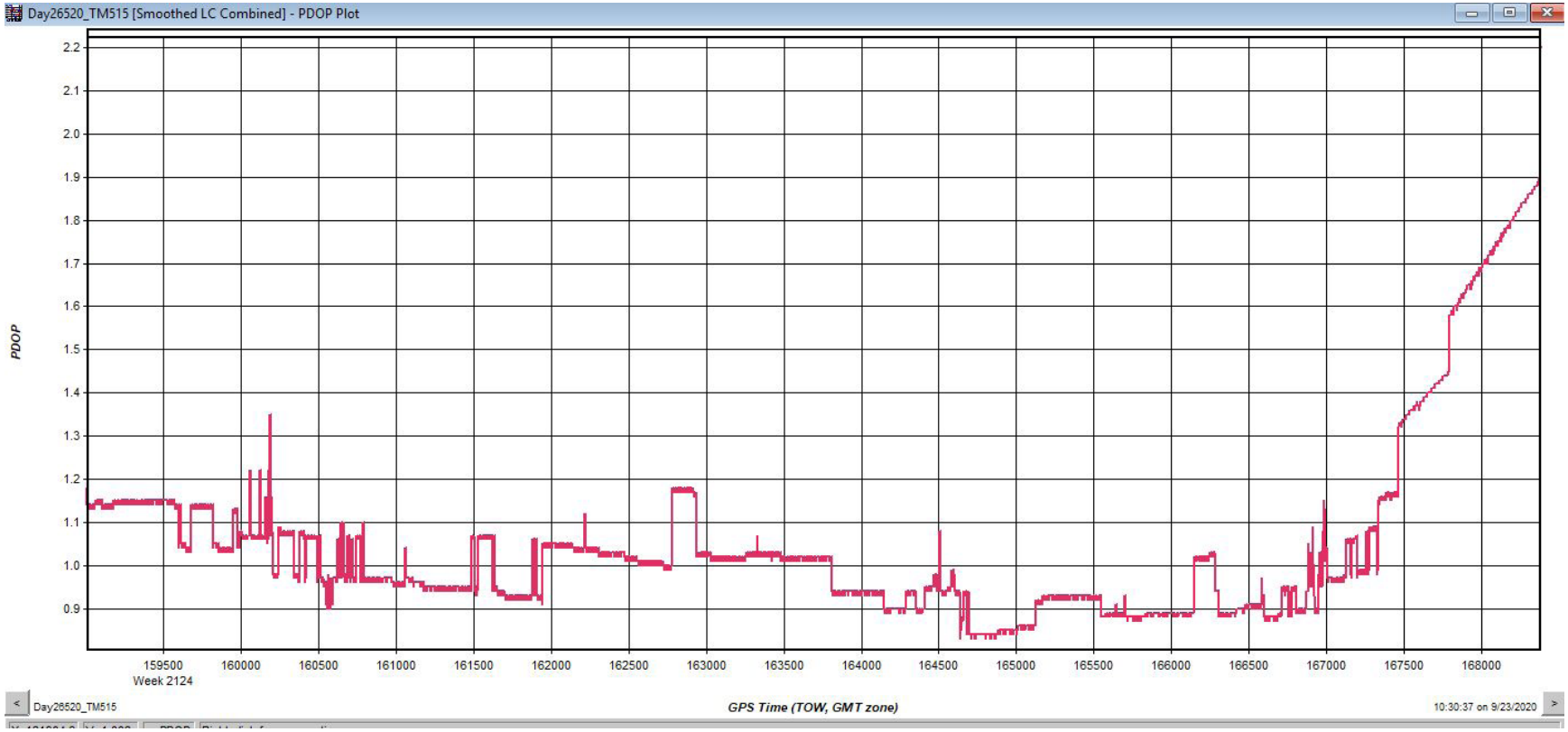
# Day27320_TM511
## Forward/Reverse or Combined Separation Plot



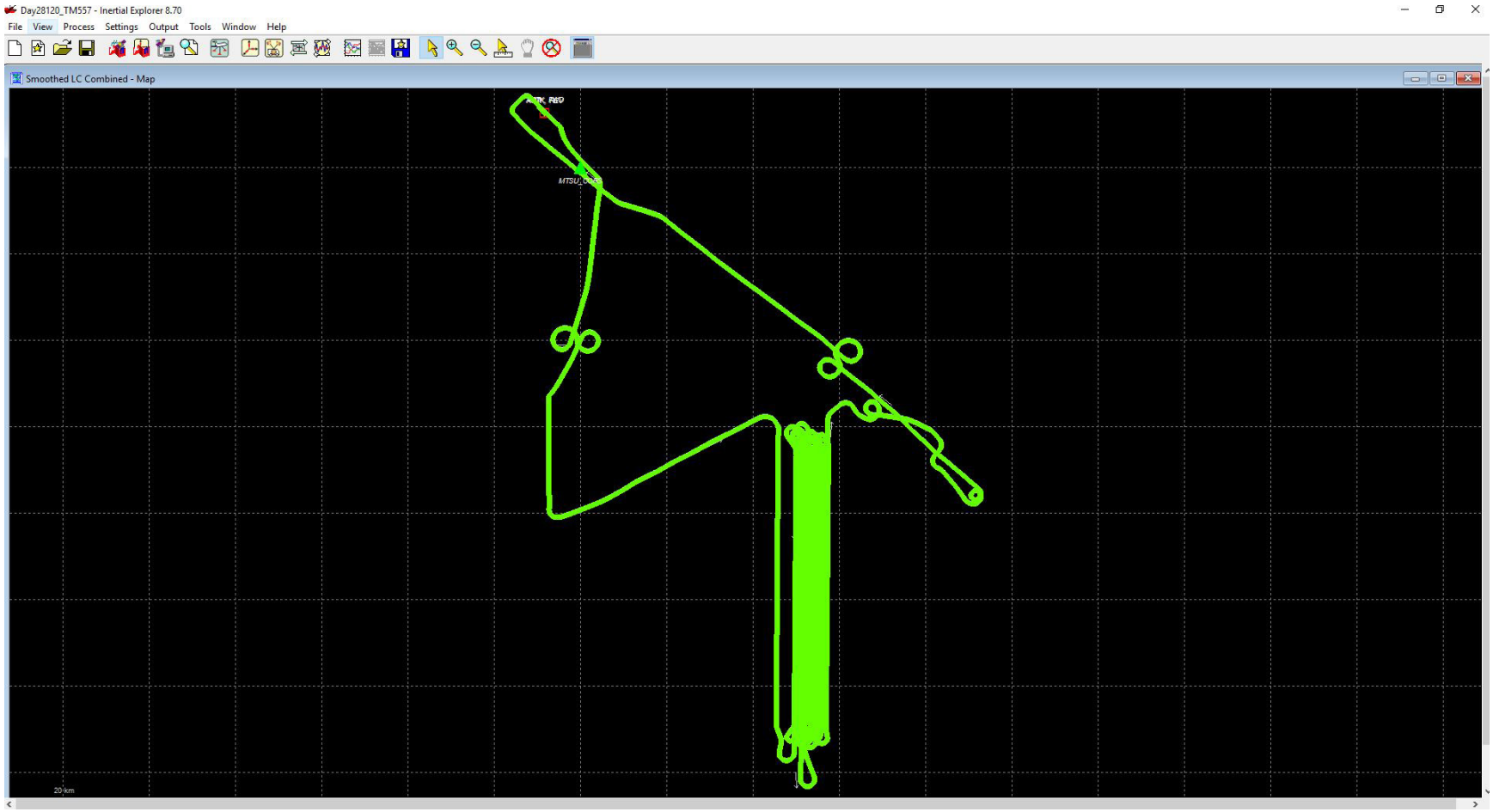
# Day27320_TM511
## Estimated Position Accuracy



# Day27320_TM511
PDOP Plot

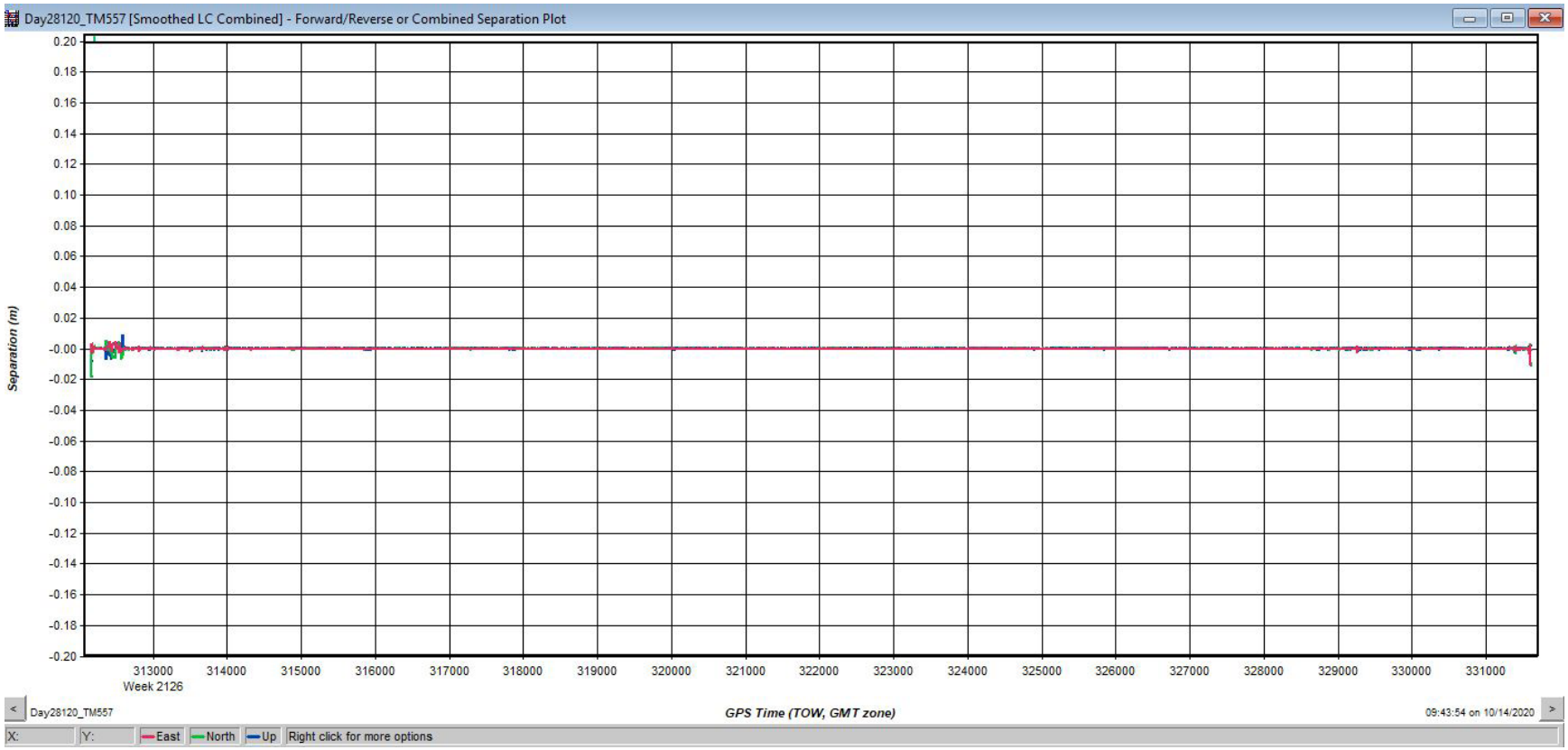


# Day28120_TM557
Trajectory

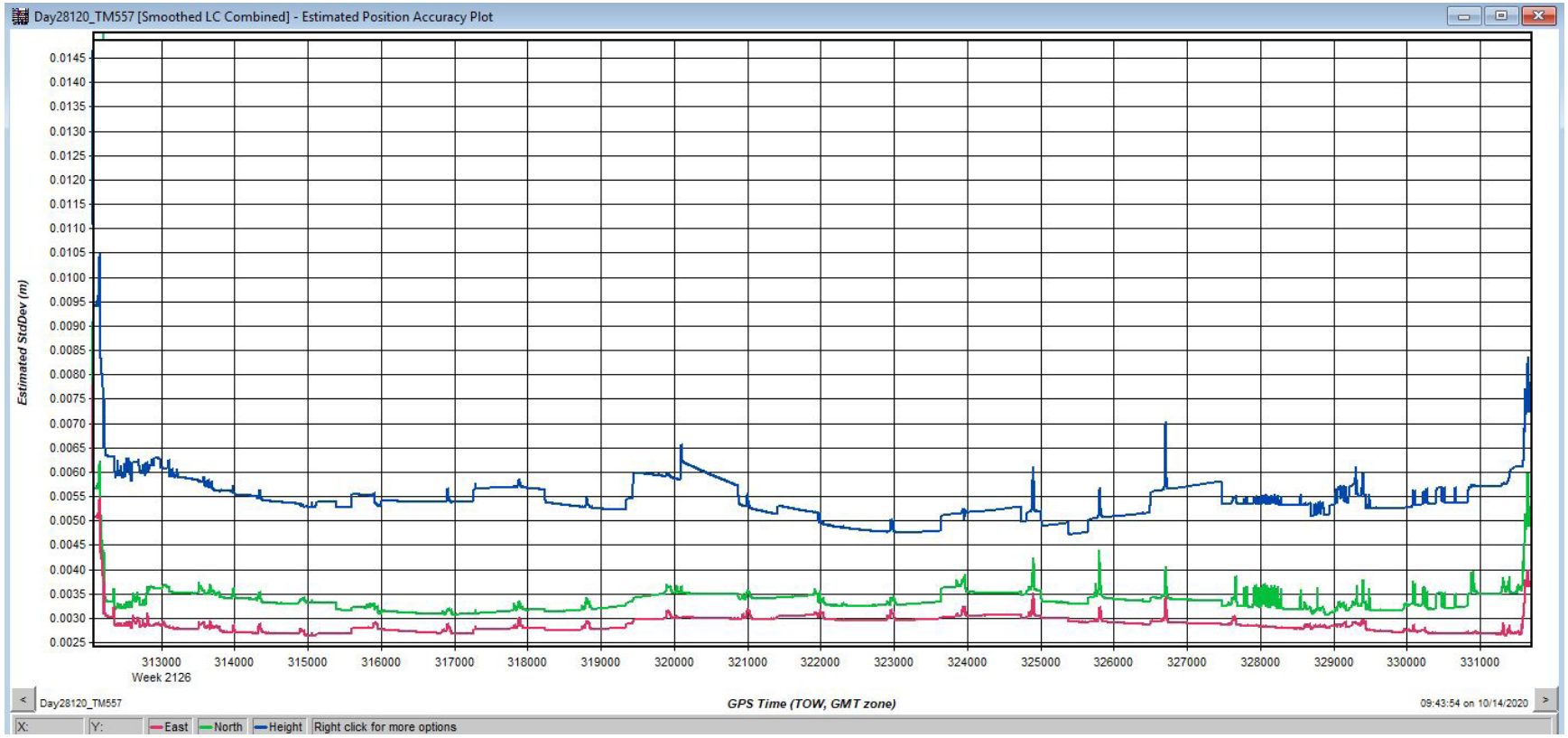


# Day28120_TM557

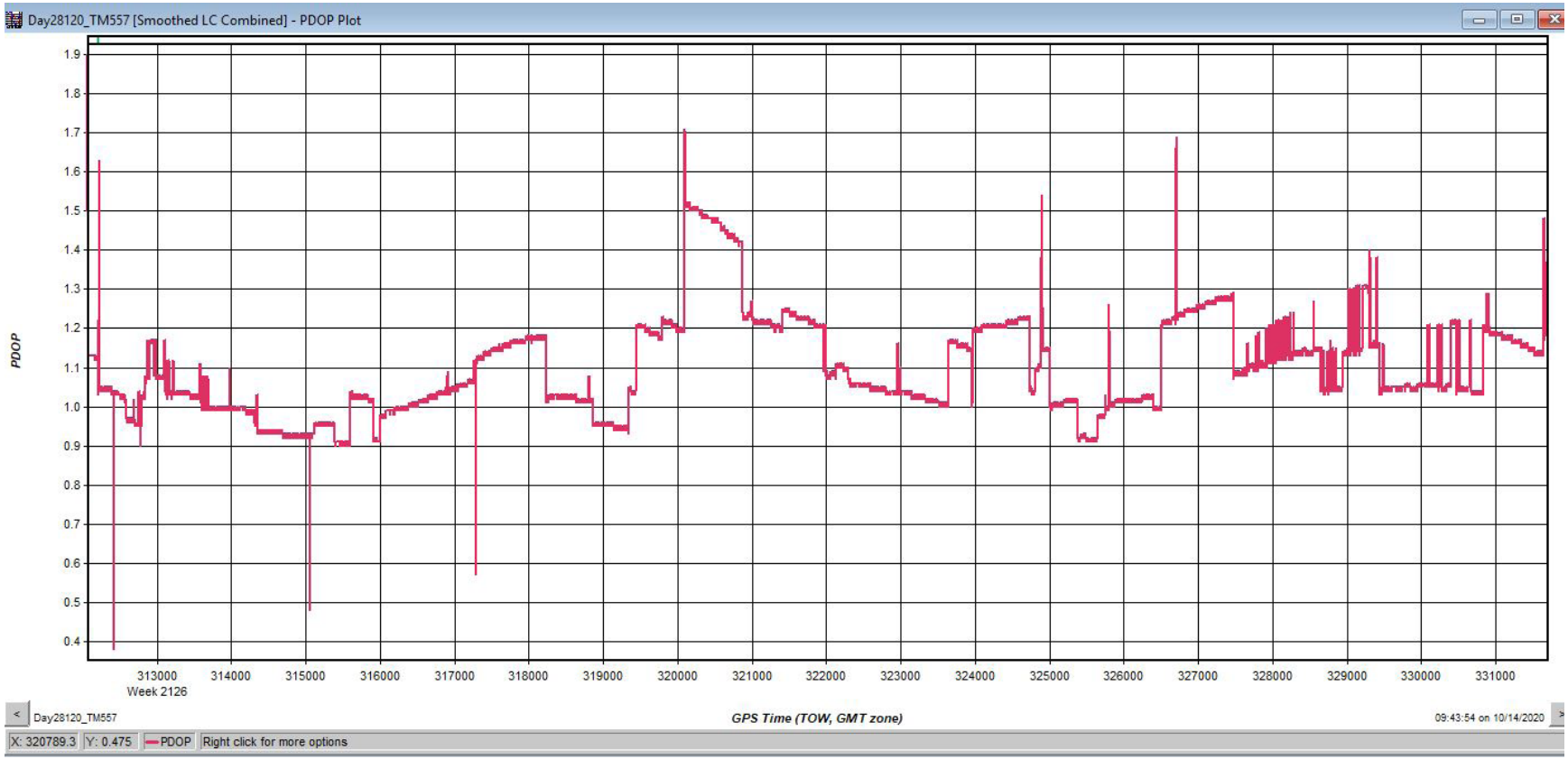
## Forward/Reverse or Combined Separation Plot



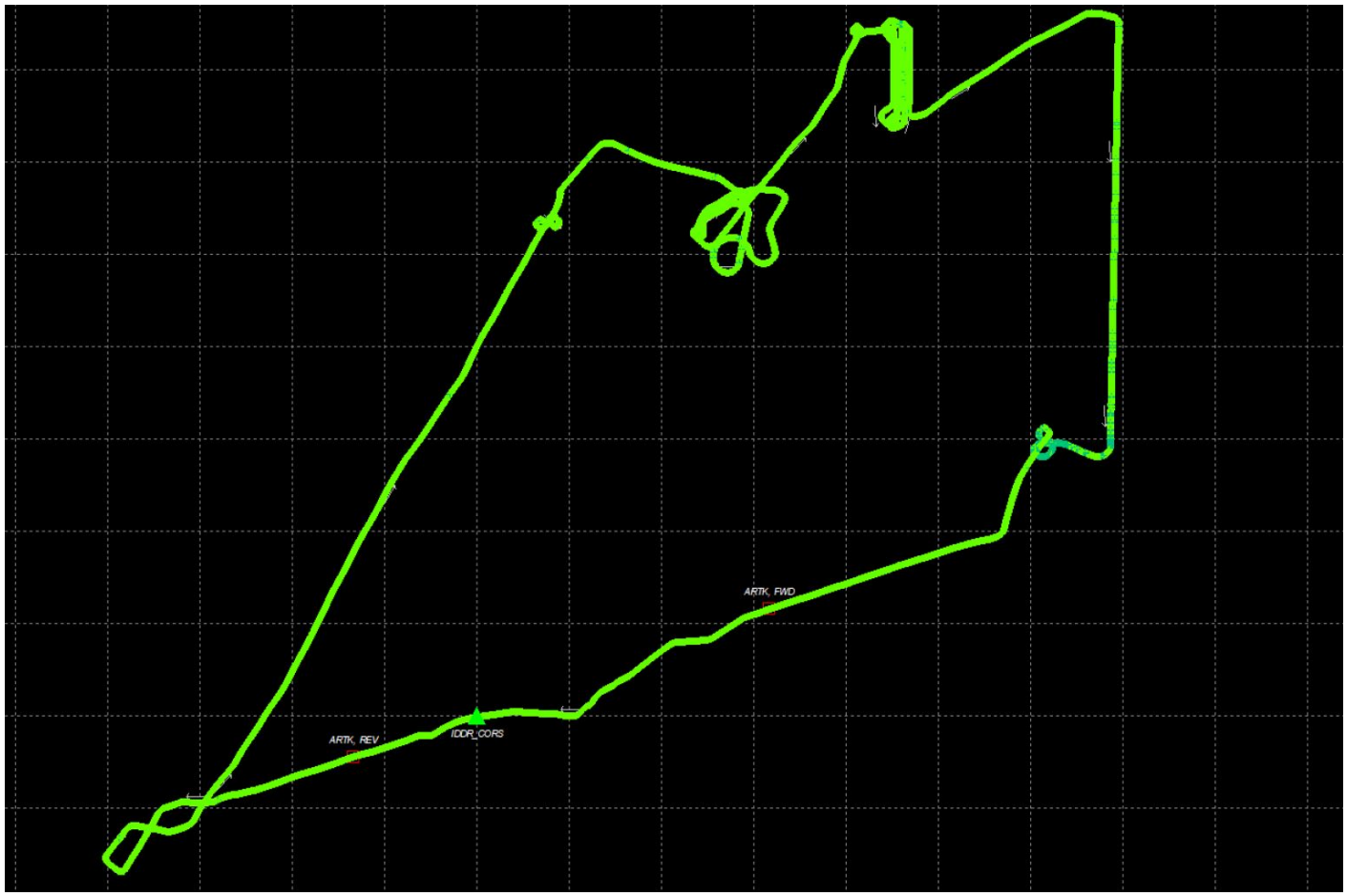
# **Day28120_TM557** Estimated Position Accuracy



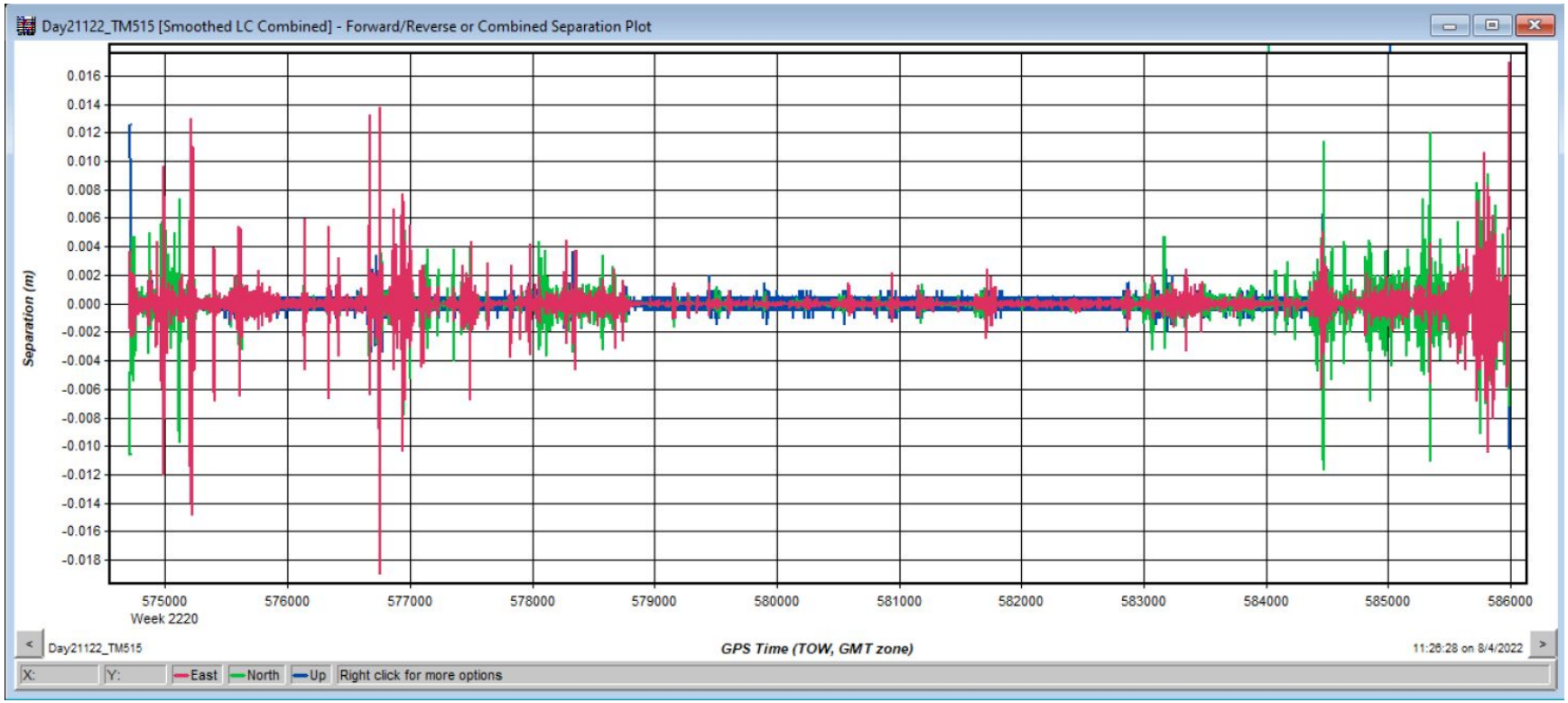
# Day28120_TM557
PDOP Plot



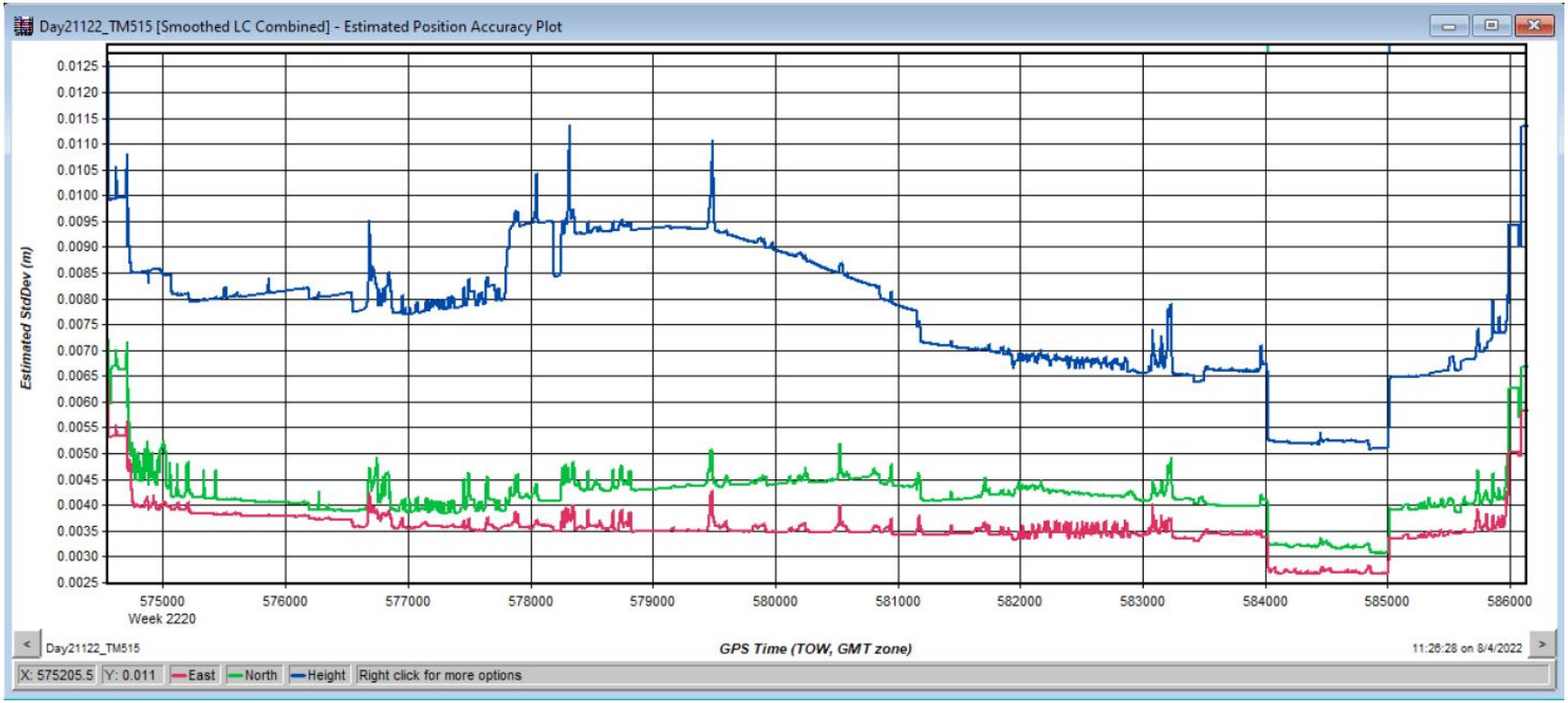
# Day21122_TM515
Trajectory



# Day21122_TM515
## Forward/Reverse or Combined Separation Plot



# **Day21122_TM515** Estimated Position Accuracy



# DayDay21122_TM515
PDOP Plot