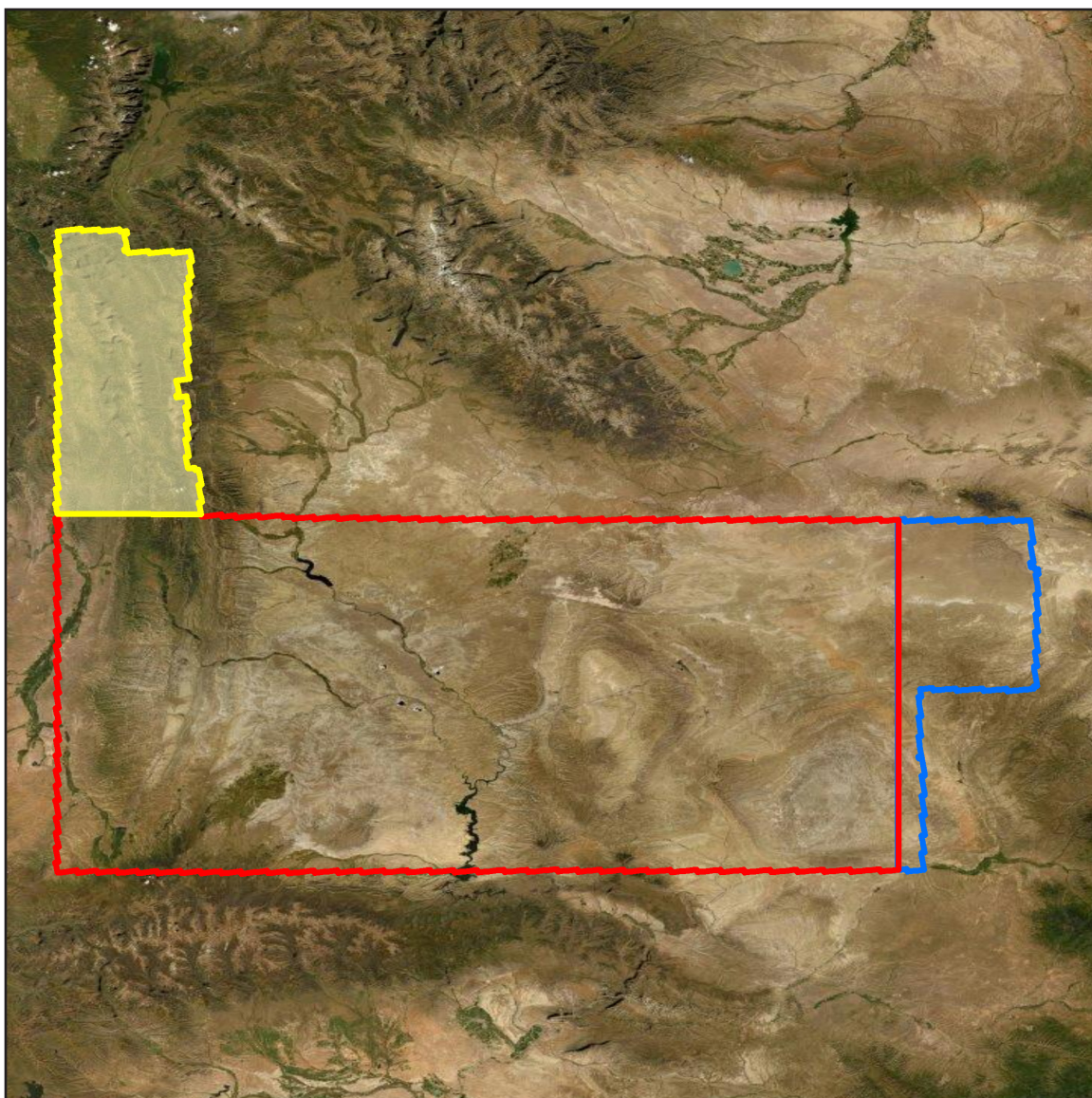


WY Southwest 2020 D20

Lidar Mapping Report

WY_Southwest_1_2020 - Work Unit 193037

February 2020



Contract # G16PC00022
Task Order # 140G0220F0107



Contractor Woolpert
Project # 80904

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1. Overview

About

This project contains a comprehensive outline of the 140G0220F0107 WY Southwest 2020 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 data over four blocks of interest covering approximately 16,952 square miles in southwestern Wyoming (Figure 1-1).

This report encompasses the Work Unit 193037 (Block 1) area of interest (Figure 1-2). This AOI totals approximately 5,828 square miles and includes the following counties:

Data includes the following counties:

- Lincoln

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.

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

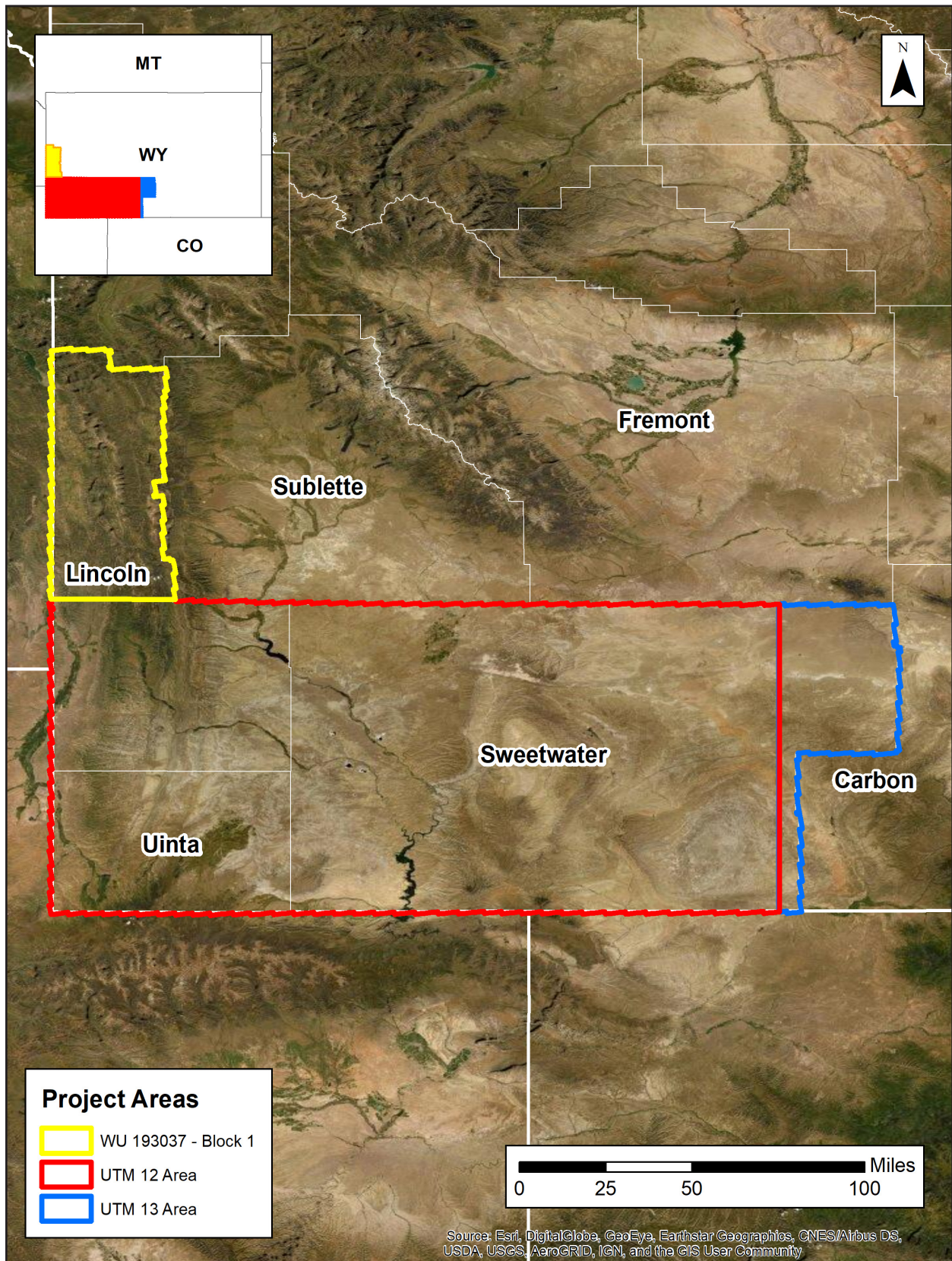
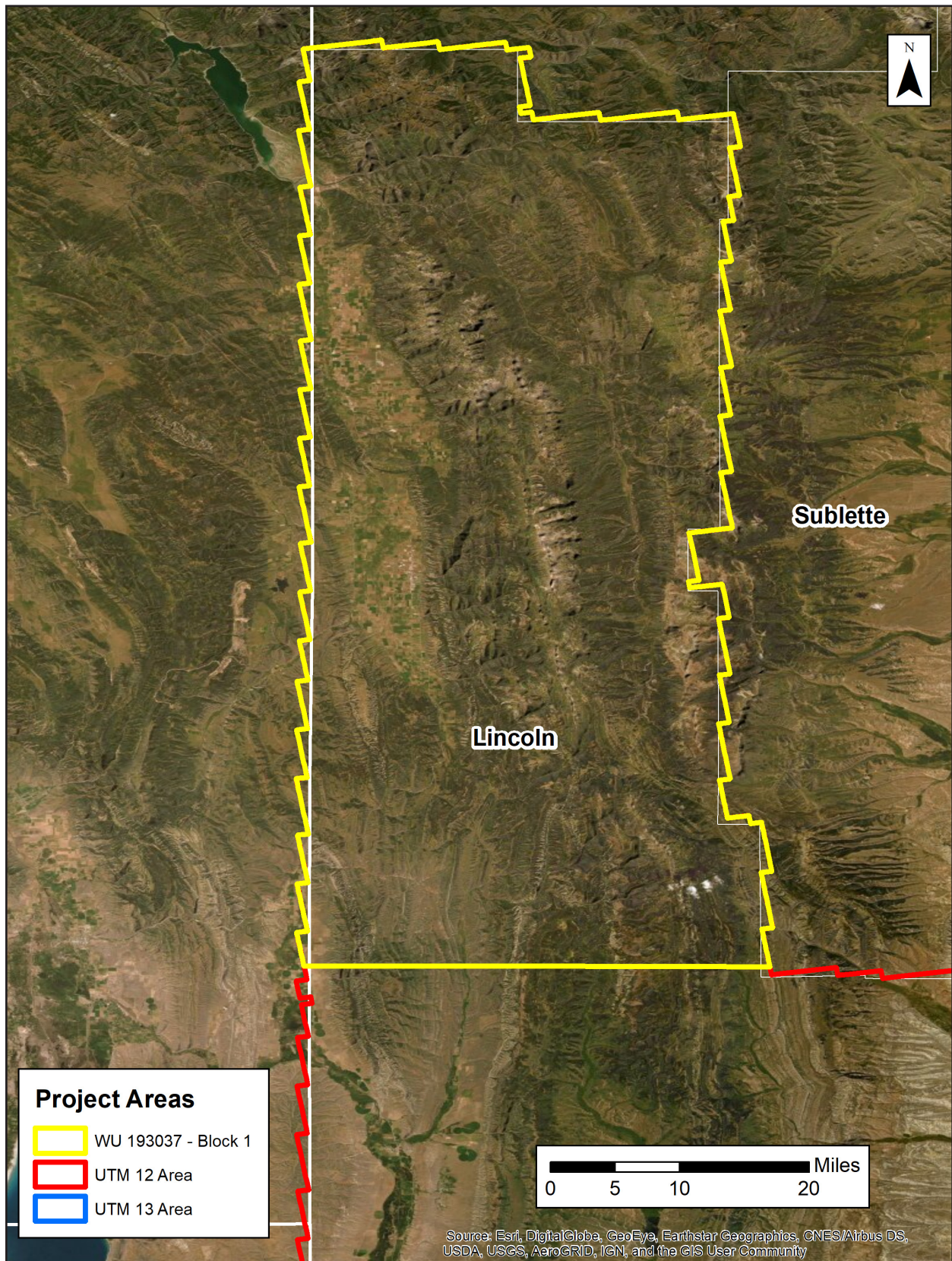


Figure 1-2. Project Area - Work Unit 193037 Block 1



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 1,000-meters x 1,000 meters. Tile names are derived from the US National Grid.

Example: 12TVM940850

This delivery's tiled dataset contains a total of 4,494 tiles. One tile was excluded from the DEM dataset as it is less than a pixel in size and the tile contained no ground points.

Excluded tiles:

- 12TWN340230

Table 1-2. Deliverables

Lidar Data	
Classified lidar point cloud data	Tiles in .las v1.4 format Classes <ul style="list-style-type: none"> • 1 – Processed, not Classified • 2 – Ground • 7 – Noise • 9 – Water • 10 – Ignored Ground • 17 – Bridge Decks • 18 – High Noise • 20 – Ignored Ground
Breaklines used for hydro-flattening	<ul style="list-style-type: none"> • Lake and River features as feature classes in an Esri file geodatabase <ul style="list-style-type: none"> • Water bodies greater than 2 acres as polygon features • Rivers 30.5 meters / 100 feet and greater in width as polyline features • Bridges used in DEM generation as point features in Esri shapefile format
Hydro-flattened bare earth digital elevation model (DEM)	1-meter pixel size, 32-bit floating-point; no bridges or overpass structures GeoTIFF format
Intensity imagery	1-meter pixel size, 8-bit gray-scale (linear rescaling from 16-bit intensity) GeoTIFF format
Control Data	
Lidar calibration points	Esri shapefile format
Lidar NVA checkpoints	Esri shapefile format
Lidar VVA checkpoints	Esri shapefile format
Spatial Data	
Data extent	Esri shapefile format
Tile index	Esri shapefile format
Interswath and intraswath results	Esri shapefile format
Swath polygons	Georeferenced, polygonal representation of the detailed extents of each lidar swath Polygon feature class in an Esri file geodatabase
Swath separation images	1-meter pixel size, 8-bit, GeoTIFF format
Other 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
Ground control survey report	Survey report 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	<ul style="list-style-type: none"> • 2 points per square meter • 0.71-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	A period of annual minimal water level in the fall 2020 leaf off window running through April, 2021
Data Voids	Not allowed except <ul style="list-style-type: none"> • Where caused by water bodies • Where caused by areas of low near infra-red (NIR) reflectivity (i.e. asphalt or composition roofing) • Where caused by lidar shadowing from buildings or other features • Where appropriately filled-in by another swath
Data Acquisition Conditions	Atmospheric <ul style="list-style-type: none"> • Cloud and fog-free between the aircraft and ground Ground <ul style="list-style-type: none"> • Snow free • No unusual flooding or inundation, except in cases where the goal of the collection is to map the inundation Vegetation <ul style="list-style-type: none"> • Leaf-off is preferred Time of Day <ul style="list-style-type: none"> • Time of day is not of concern

Flight plans were created using Leica MissionPro software.

Lidar Sensor Information

Aerial lidar data was acquired using the following lidar sensor system:

- Leica TerrainMapper - serial number 90515, last calibrated July 3, 2019

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

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) • Scanner • Control Electronics	<ul style="list-style-type: none"> • 37 W x 68 L x 26 H cm, 47 kg • 45 W x 47 D x 25 H cm, 33 kg
Operating Temperature • Scanner • Control Electronics	<ul style="list-style-type: none"> • 0 - 40°C cabin-side temperature • 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	Leica TerrainMapper
Max. Number of Returns	15
Nominal Point Spacing	0.71 m
Nominal Point Density	2 ppsm
Flying Height Above Ground Level	3,000 m
Flight Speed	150 knots
Scan Angle	40°
Scan Rate Used	82 Hz
Pulse Rate Used	600 kHz
Multi-Pulse in Air	Enabled
Swath Width	2,184 m
Swath Overlap	20%

Timeline

Lidar data was collected from August 11, 2020 through August 25, 2020. A total of 83 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 2-4 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 with Tile Index

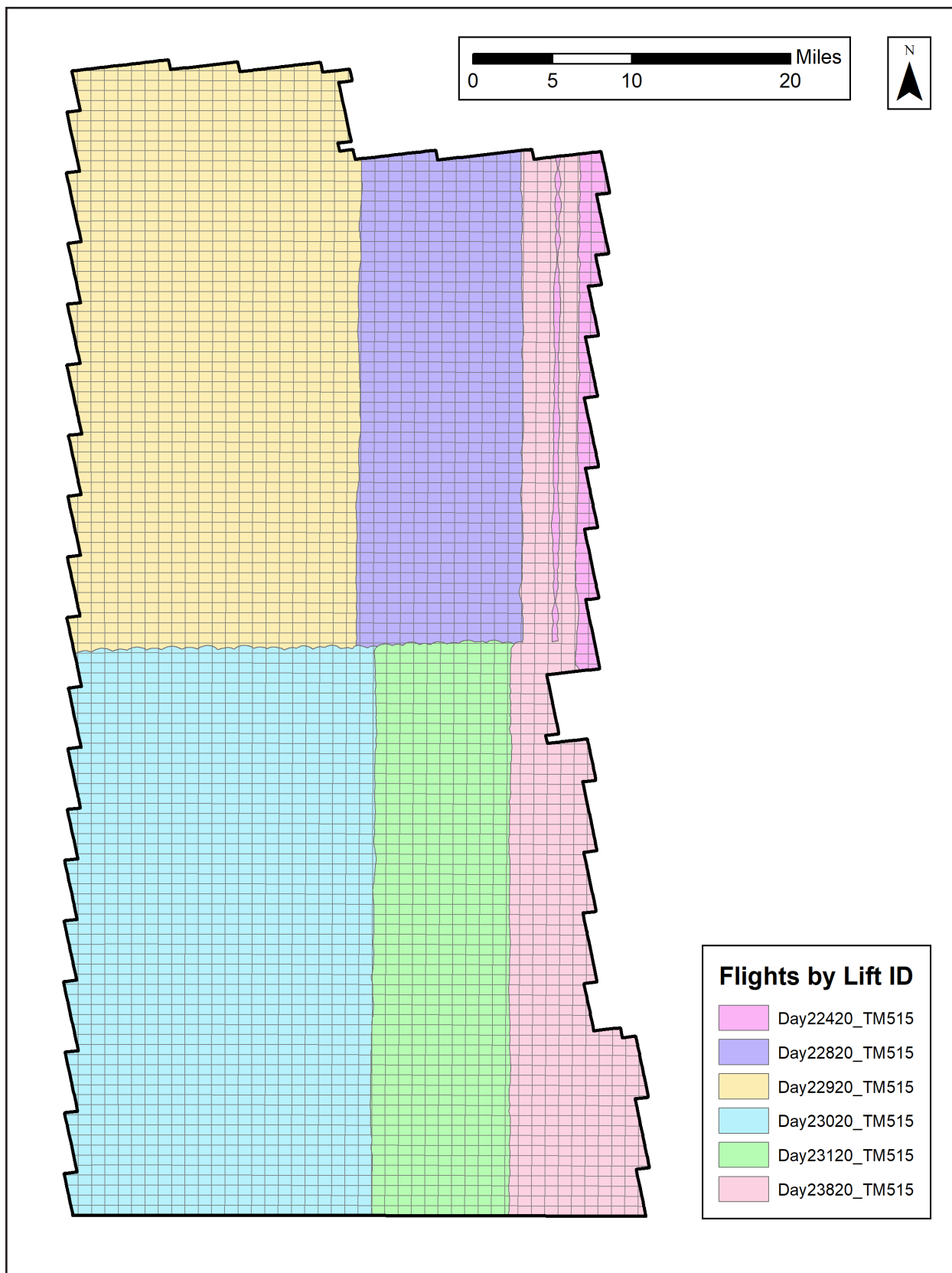


Table 2-4. GNSS Base Stations

Station Name	Longitude (DMS)	Latitude (DMS)	Ellipsoid Height L1 Phase Center (Meters)
P030_CORR	-110° 30' 46.06698"	41° 44' 59.31530"	2150.596
TSWY_CORR	-110° 36' 50.86433"	43° 40' 26.70325"	2191.496
BLW2_CORR	-109° 33' 28.03604"	42° 46' 01.63709"	2216.398
IDDR_CORR	-111° 06' 36.92145"	43° 44' 46.00161"	1864.684

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 $(4 \times \text{ANPS})^2$ exhibited data coverage gaps.

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 Reports 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)
-0.050	0.070	0.023
-0.065	0.070	0.029
-0.090	0.080	0.037
-0.070	0.080	0.031
-0.070	0.050	0.022

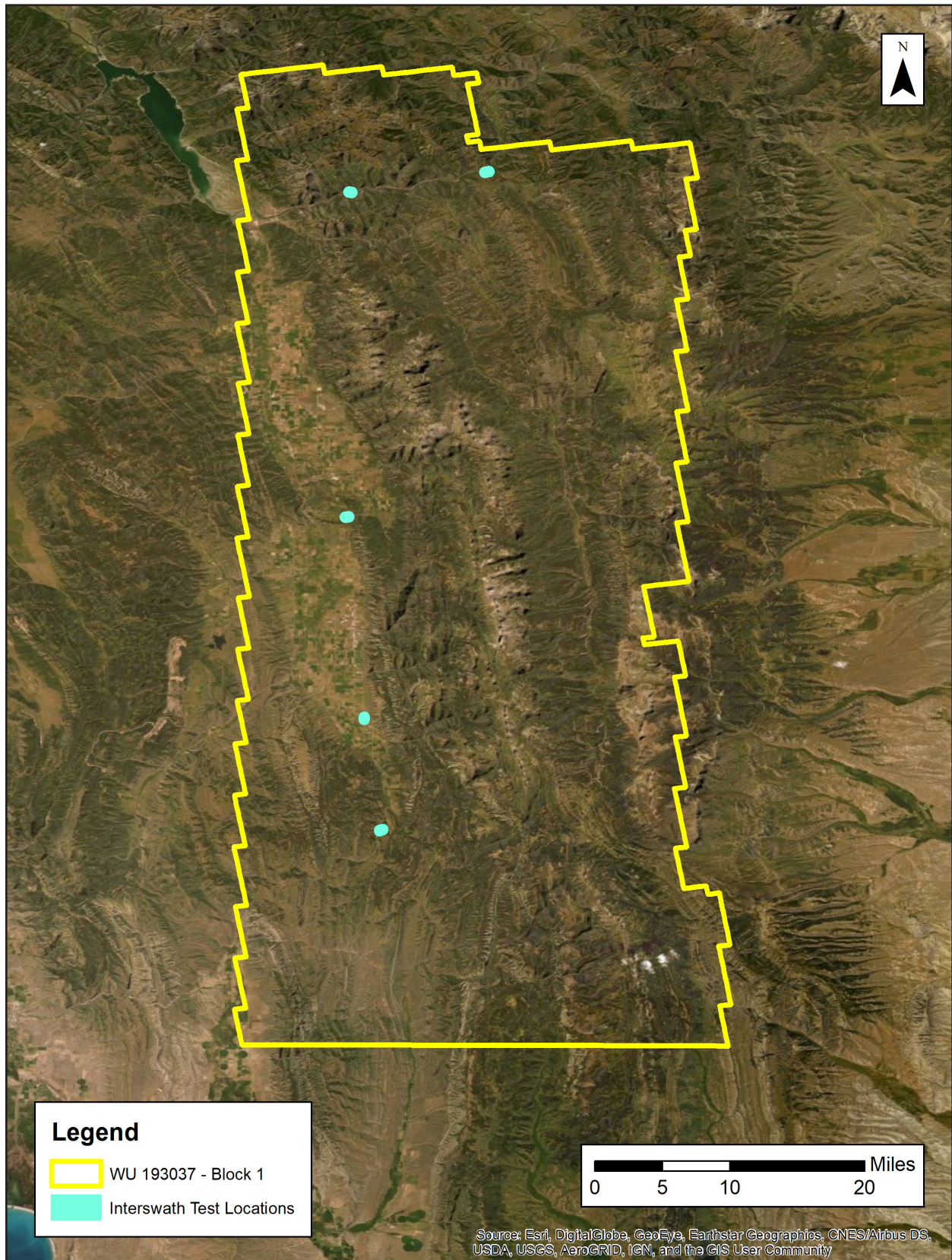
Swath Separation Images

All point returns (except those flagged as withheld or classified as noise) were used to create a swath separation image covering the deliverable area. The imagery was derived from TIN datasets to reduce the number of false difference values on sloped areas. This imagery metadata denotes areas where two or more swaths overlap within a pixel, based on the point source ID. Pixels are assigned color values based on the vertical difference of the swaths based on the following:

0 - 8 cm	Green
8 - 16 cm	Yellow
> 16 cm	Red

Swath separation images were produced with a 2-meter cell size in GeoTIFF format.

Figure 3-1. Interswath Testing Locations



Relative Accuracy: Intrawath Precision

Intrawath 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.

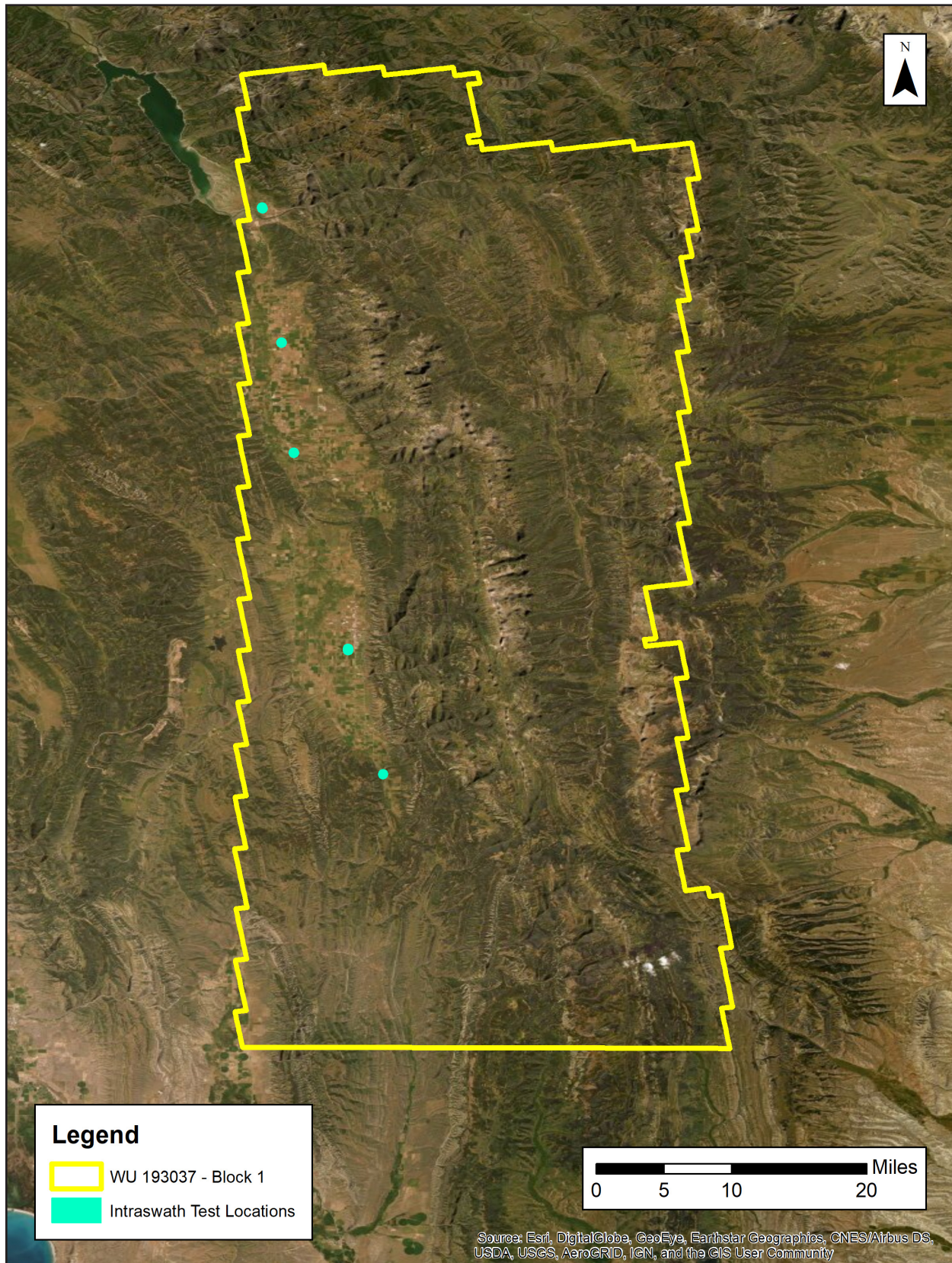
This project required the intrawath accuracy to meet ≤ 6 cm RMSDz. Accuracy was assessed in accordance with the USGS Base Specification v2020 revision A.

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

Table 3-2. Intrawath Results

Minimum (m)	Maximum (m)	RMSDz (m)
-0.890	0.052	0.042
-0.044	0.067	0.021
-0.061	0.052	0.022
-0.151	0.089	0.046
-0.081	0.068	0.029

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 total number of points within each class.

Table 3-3. Lidar Point Classes

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

The lidar task order required compilation of breaklines defining the following types of water body features:

Lakes, reservoirs, ponds	Minimum of 2-acres or greater Compiled as closed polygons, collected at a constant elevation
Rivers, streams	Nominal width of 30.5 meters / 100 feet Compiled in direction of flow, with both sides maintaining an equal elevation gradient
Bridge breaklines	Breaklines used to enforce a logical terrain surface below a bridge

Woolpert utilized the following steps to hydrologically flatten the water bodies and for gradient hydrologic flattening of the double line streams within the existing lidar data:

1. The newly acquired lidar data was utilized to manually compile the hydrologic features in a 2D environment using the lidar intensity and bare earth surface. Open Source imagery was used as reference when necessary.
2. An integrated software approach was applied to combine the lidar data and 2D breaklines. This process “drapes” the 2D breaklines onto the 3D lidar surface model to assign an elevation. A monotonic process is performed to ensure the streams are consistently flowing in a gradient manner. A secondary step within the program verifies an equally matching elevation of both stream edges. The breaklines that characterize the closed water bodies are draped onto the 3D lidar surface and assigned a constant elevation at or just below ground elevation.
3. All classified ground points from inside the hydrologic feature polygons were reclassified to water, class nine (9).
4. All classified ground points were reclassified from within a buffer along the hydrologic feature breaklines to buffered ground, class twenty (20). The buffer distance was approximately the task order designed nominal pulse spacing distance.
5. Breaklines used for bridge removal during the hydrologic flattening were included with the hydrologic breakline geodatabase deliverable. The purpose of these breaklines is for a more aesthetically pleasing DEM appearance.
6. The lidar ground points and breaklines were used to generate a digital elevation model (DEM).
7. QA/QC for this task was performed by reviewing the hydrologically flattened DEM and hydrologic breakline features. Additionally, a combined approach utilizing commercial off the shelf software and proprietary methods were used to review the overall connectivity of the hydrologic breaklines.

TerraScan was used to add the hydrologic breakline vertices and export the lattice models.

Breaklines defining the water bodies greater than 2-acres were provided as polygon features. Rivers and streams with a nominal minimum width of 30.5 meters (100 feet) were provided as polyline features. All lake and river breaklines compiled as part of the flattening process were provided in an Esri file geodatabase.

Breaklines used for DEM generation were provided as point features in Esri shapefile format.

Software: TerraScan v20, TerraModeler v20, Esri ArcMap v10.7, LP360 v2019.1.30.4

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 1-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 1-meter pixel, 8-bit, 256 gray scale GeoTIFF format intensity imagery files. Files were clipped to the data extent.

Software: TerraScan v20, GDAL 2.4.0, 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 Esri shapefiles of the ground control and QA/QC points, interswath and intraswath test results, data extent, and 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.

4. Accuracy Assessment

Horizontal Accuracy

The data set was produced to meet ASPRS “Positional Accuracy Standards for Digital Geospatial Data” (2014) for a 0.162 cm RMSE_x / RMSE_y Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 0.397 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 RMSE_z 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 RMSE _z 0.067 m at 95% CL	47
VVA	0.220 at 95th Percentile	23

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 RMSE_z target value of 10 cm x 1.9600. VVA was required to meet 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 Vertical Accuracy

	Result	Points Used
NVA	0.033 m RMSEz 0.065 m at 95% CL	47
VVA	0.204 at 95th Percentile	23

Appendix 1: Sensor Calibration Report

- when it has to be **right**



Leica Geosystems

Leica TerrainMapper-LN

Calibration Certificate

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






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 Misalignment 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
Rotation Axis	Speed Pitch	1.50E-06	degree/rps ²
	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 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

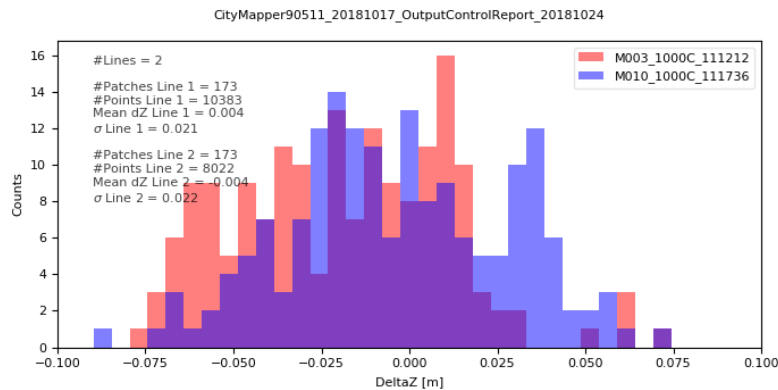


Figure 1 Vertical distance to ground control points at 1000 m AGL.

5.2.2 Difference of forward and backward scan of one line

M010_1000C_111736

314314 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 [%]
Green	≤ 0.04	293823	93.48
Yellow	0.04-0.07	20386	6.49
Orange	0.07-0.1	89	0.03
Red	> 0.1	16	0.01



Figure 2 Vertical difference between 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

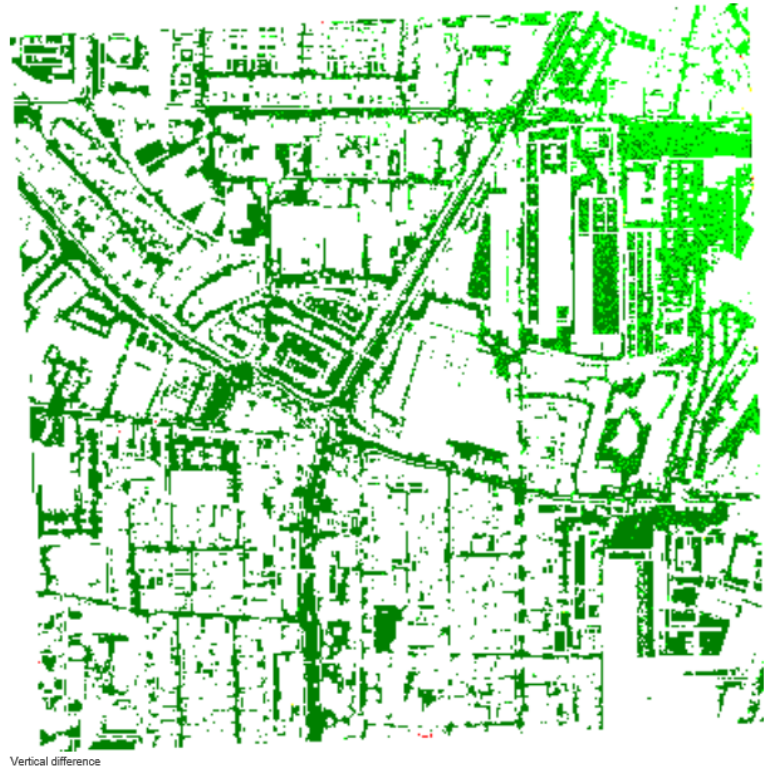


Figure 3 Vertical difference between two perpendicular lines at 1000 m AGL.

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

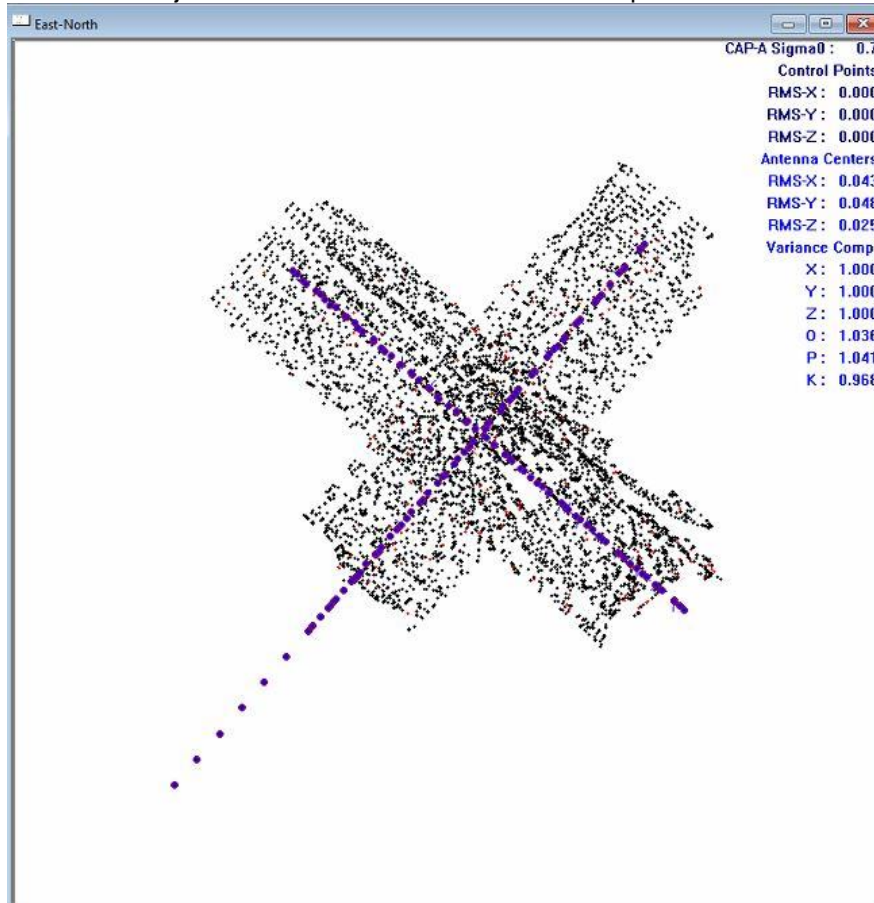
Reference band (green)

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

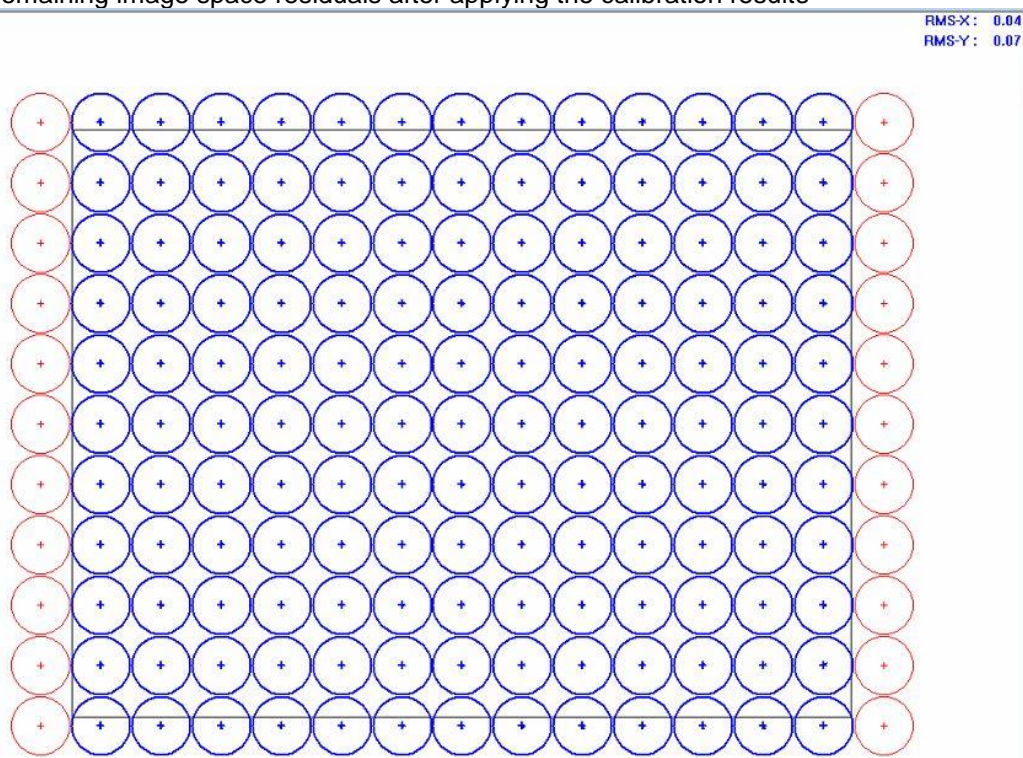
	Component	Serial Number
Camera Head	CH82	82659
Lens	NAT-D 2.8/80	80254
View Direction in Pod Position	Nadir	
IMU Misalignment	Angle [degree]	
	ω	-0.00815
	ϕ	0.00028
	κ	-0.26654
Principal Point	Distance [mm]	
	x	0.0000
	y	0.0000
Focal Length	Distance [mm]	
	c	83.00

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
Misalignment Flight	Date	23.06.2019
Misalignment Update Completed	Date	02.07.2019

Remaining image space residuals after applying the calibration results



Radius of circles is 0.0007 mm

Appendix 2: Flight Logs

[illegible]

[illegible]

Woolpert Lidar Acquisition Log

Project Info							Date		
Project #	Project Name		Unique ID		Flight Date (UTC)	Day of Year	Flight #		
80904	South West Wyoming		Day229_90515_A		08/16/2020	229	A		
Crew		Equipment		Time			Airports		
Pilot	Aircraft Make / Model / Tail #		Hobbs Start	Local Start	UTC Start	Departing			
Gilibaro	Cessna 404 Titan - N7079F		2821	07:38:00	13:38:00	KJAC			
Operator	Sensor Make / Model / Serial #		Hobbs End	Local End	UTC End	Arriving			
DeHart	Leica Terrain Mapper - 90515		2828	01:46:00	19:46:00	KJAC			
Conditions									
Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)		
0	0	10	12,000	Clear	4	-0.6	30.46		
Air Speed (kts)		Altitude AGL (ft)	Altitude MSL (ft)	Airfield Elevation (ft)					
160		7,908	15,427	6,451					
Settings									
Point Spacing (m)	Point Density (ppsm)	Scan Angle/FOV (°)	Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)				
0.35	10	40	89	600	100				
							Verify S-Turns Before Mission	Yes	
Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments		
21	S	13:38:00	13:52:00	00:14:00	17	1.4	Block 1		
20	N	13:56:00	14:10:00	00:14:00	17	1.4			
19	S	14:13:00	14:28:00	00:15:00	21	1			
18	N	14:31:00	14:45:00	00:14:00	21	1			
17	S	14:49:00	15:03:00	00:14:00	19	1.2			
16	N	15:07:00	15:21:00	00:14:00	20	1.2			
15	S	15:24:00	15:39:00	00:15:00	21	1.1			
14	N	15:42:00	15:56:00	00:14:00	22	1.1			
13	S	15:58:00	16:13:00	00:15:00	20	1.2			
12	N	16:16:00	16:32:00	00:16:00	19	1.7			
11	S	16:35:00	16:49:00	00:14:00	19	1.7			
10	N	16:53:00	17:08:00	00:15:00	18	2.1			
9	S	17:11:00	17:25:00	00:14:00	19	1.4			
8	N	17:28:00	17:42:00	00:14:00	16	1.4			
7	S	17:45:00	17:59:00	00:14:00	18	1.2			
6	N	18:03:00	18:19:00	00:16:00	22	1.2			
5	S	18:22:00	18:36:00	00:14:00	22	1.2			
4	N	18:39:00	18:54:00	00:15:00	20	1.3			
3	S	18:57:00	19:11:00	00:14:00	20	1.3			
2	N	19:14:00	19:29:00	00:15:00	21	1.2			
1	S	19:32:00	19:46:00	00:14:00	19	1.3			
Page 1							Verify S-Turns After Mission	Yes	
Additional Comments									

Woolpert Lidar Acquisition Log										
Project Info							Date			
Project #	Project Name			Unique ID			Flight Date (UTC)	Day of Year	Flight #	
80904	South West Wyoming			Day230_90515_A			08/17/2020	230	A	
Crew		Equipment			Time			Airports		
Pilot	Aircraft Make / Model / Tail #			Hobbs Start		Local Start	UTC Start	Departing		
Gilibaro	Cessna 404 Titan - N7079F			2828		07:56:00	13:56:00	KJAC		
Operator	Sensor Make / Model / Serial #			Hobbs End		Local End	UTC End	Arriving		
DeHart	Leica Terrain Mapper - 90515			2834.1		01:09:00	19:09:00	KJAC		
Conditions										
Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)			
0	0	10	12,000	Clear	7.8	-0.6	30.5			
Air Speed (kts)		Altitude AGL (ft)		Altitude MSL (ft)		Airfield Elevation (ft)				
160		7,908		15,427		6,451				
Settings										
Point Spacing (m)	Point Density (ppsm)		Scan Angle/FOV (°)		Scan Frequency (Hz)		Pulse Rate (kHz)	Laser Power (%)		
0.35	10		40		89		600	100		
							Verify S-Turns Before Mission		Yes	
Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments			
1	S	13:56:00	14:09:00	00:13:00	18	1.5	Block 2			
2	N	14:12:00	14:25:00	00:13:00	19	1.5				
3	S	14:28:00	14:41:00	00:13:00	23	1.2				
4	N	14:44:00	14:57:00	00:13:00	21	1.3				
5	S	15:00:00	15:12:00	00:12:00	22	1.2				
6	N	15:15:00	15:28:00	00:13:00	23	1.2				
7	S	15:31:00	15:44:00	00:13:00	23	1.2				
8	N	15:47:00	15:59:00	00:12:00	21	1.5				
9	S	16:02:00	16:15:00	00:13:00	23	1.1				
10	N	16:18:00	16:30:00	00:12:00	21	1.3				
11	S	16:33:00	16:46:00	00:13:00	21	1.3				
12	N	16:49:00	17:02:00	00:13:00	21	1.2				
13	S	17:05:00	17:18:00	00:13:00	20	1.2				
14	N	17:21:00	17:33:00	00:12:00	18	1.6				
15	S	17:36:00	17:49:00	00:13:00	20	1.4				
16	N	17:52:00	18:05:00	00:13:00	20	1.3				
17	S	18:08:00	18:21:00	00:13:00	22	1.2				
18	N	18:24:00	18:37:00	00:13:00	24	1.2				
19	S	18:40:00	18:53:00	00:13:00	21	1.3				
20	N	18:56:00	19:09:00	00:13:00	19	1.2				
Page 1							Verify S-Turns After Mission		Yes	
Additional Comments										

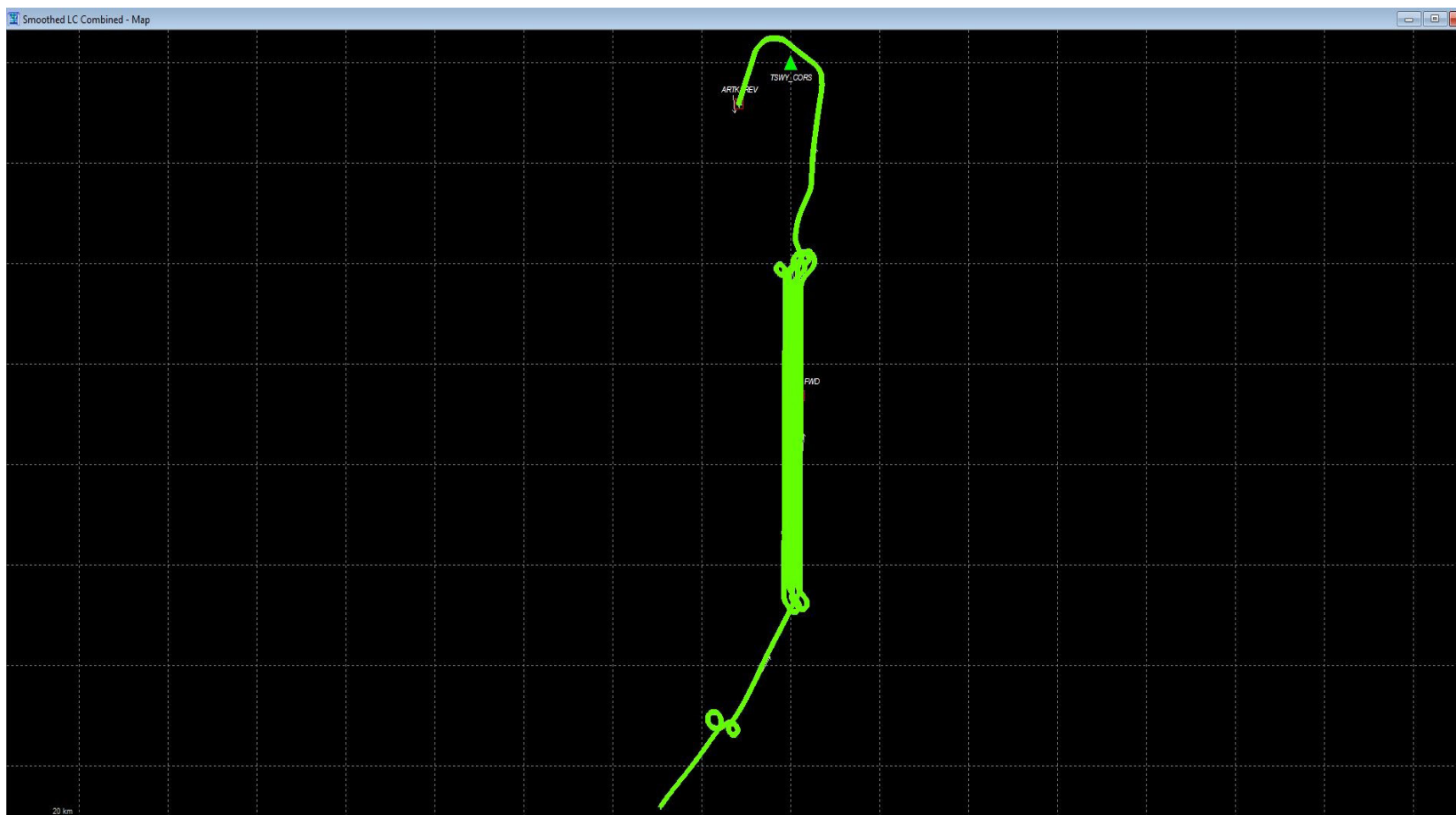
[illegible]

Woolpert Lidar Acquisition Log								
Project Info						Date		
Project #	Project Name			Unique ID		Flight Date (UTC)	Day of Year	Flight #
80904	South West Wyoming			Day238_90515_A		08/25/2020	238	A
Crew		Equipment			Time			Airports
Pilot	Aircraft Make / Model / Tail #			Hobbs Start	Local Start	UTC Start	Departing	
Gilibaro	Cessna 404 Titan - N7079F			2840.5	08:14:00	14:14:00	KJAC	
Operator	Sensor Make / Model / Serial #			Hobbs End	Local End	UTC End	Arriving	
DeHart	Leica Terrain Mapper - 90515			2844.8	11:46:00	17:46:00	KJAC	
Conditions								
Wind Dir (°)	Wind Speed (kts)	Visibility (mi)	Ceiling (ft)	Cloud Cover	Temp. (°C)	Dew Point (°C)	Pressure ("Hg)	
0	0	10	12,000	Overcast	10	7.8	30.26	
Air Speed (kts)		Altitude AGL (ft)		Altitude MSL (ft)		Airfield Elevation (ft)		
160		7,908		15,427		6,451		
Settings								
Point Spacing (m)	Point Density (ppsm)		Scan Angle/FOV (°)		Scan Frequency (Hz)	Pulse Rate (kHz)	Laser Power (%)	
0.35	10		40		89	600	100	
						Verify S-Turns Before Mission		Yes
Line #	Direction	Start Time (UTC)	End Time (UTC)	Time On-Line	Satellite	PDOP	Line Notes/Comments	
35	S	14:14:00	14:27:00	00:13:00	17	1.1	Block 1	
36	N	14:30:00	14:42:00	00:12:00	16	1.3		
38	S	14:46:00	14:58:00	00:12:00	19	1.2		
31	S	15:04:00	15:17:00	00:13:00	18	1.3	Block 2	
32	N	15:19:00	15:32:00	00:13:00	18	1.3		
33	S	15:35:00	15:48:00	00:13:00	20	1.1		
34	N	15:51:00	16:04:00	00:13:00	19	1.2	roll limit at 2.5 mile mark north side	
34	S	16:07:00	16:08:00	00:01:00	19	1.3	Reflight	
35	S	16:13:00	16:26:00	00:13:00	19	1.3		
36	N	16:28:00	16:39:00	00:11:00	21	1.1		
37	S	16:42:00	16:53:00	00:11:00	20	1.5		
38	N	16:56:00	17:08:00	00:12:00	20	1.5		
39	S	17:15:00	17:15:00	24:00:00	25	1.3	Cloud on line will reflly below clouds	
41	N	17:23:00	17:28:00	00:05:00	22	1.1		
40	S	17:32:00	17:37:00	00:05:00	22	1.2		
39	N	17:40:00	17:46:00	00:06:00	23	1.2		
Page 1						Verify S-Turns After Mission		Yes
Additional Comments								
<div></div>								

Appendix 3: GPS / IMU Graphics

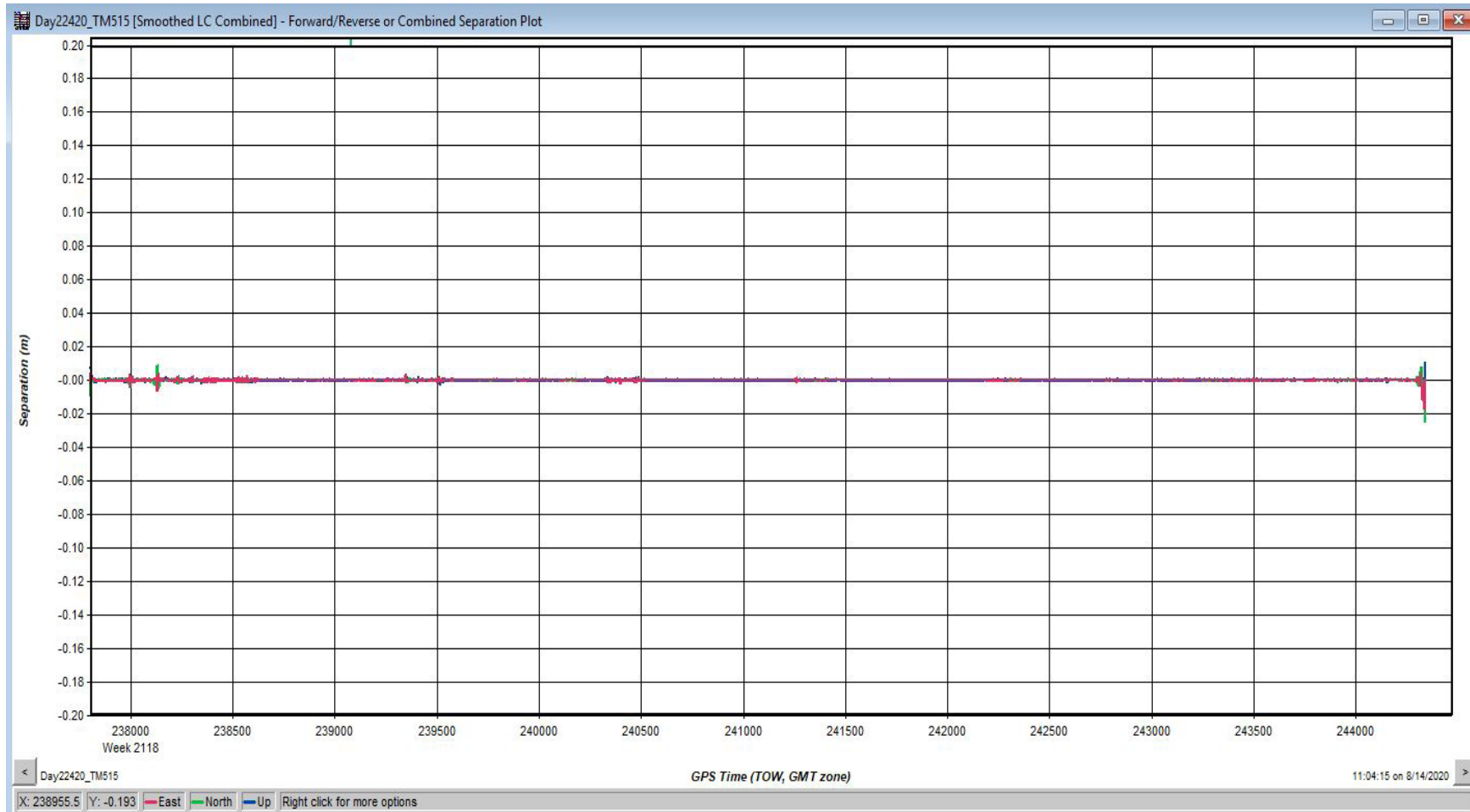
Day224420_TM515

Trajectory



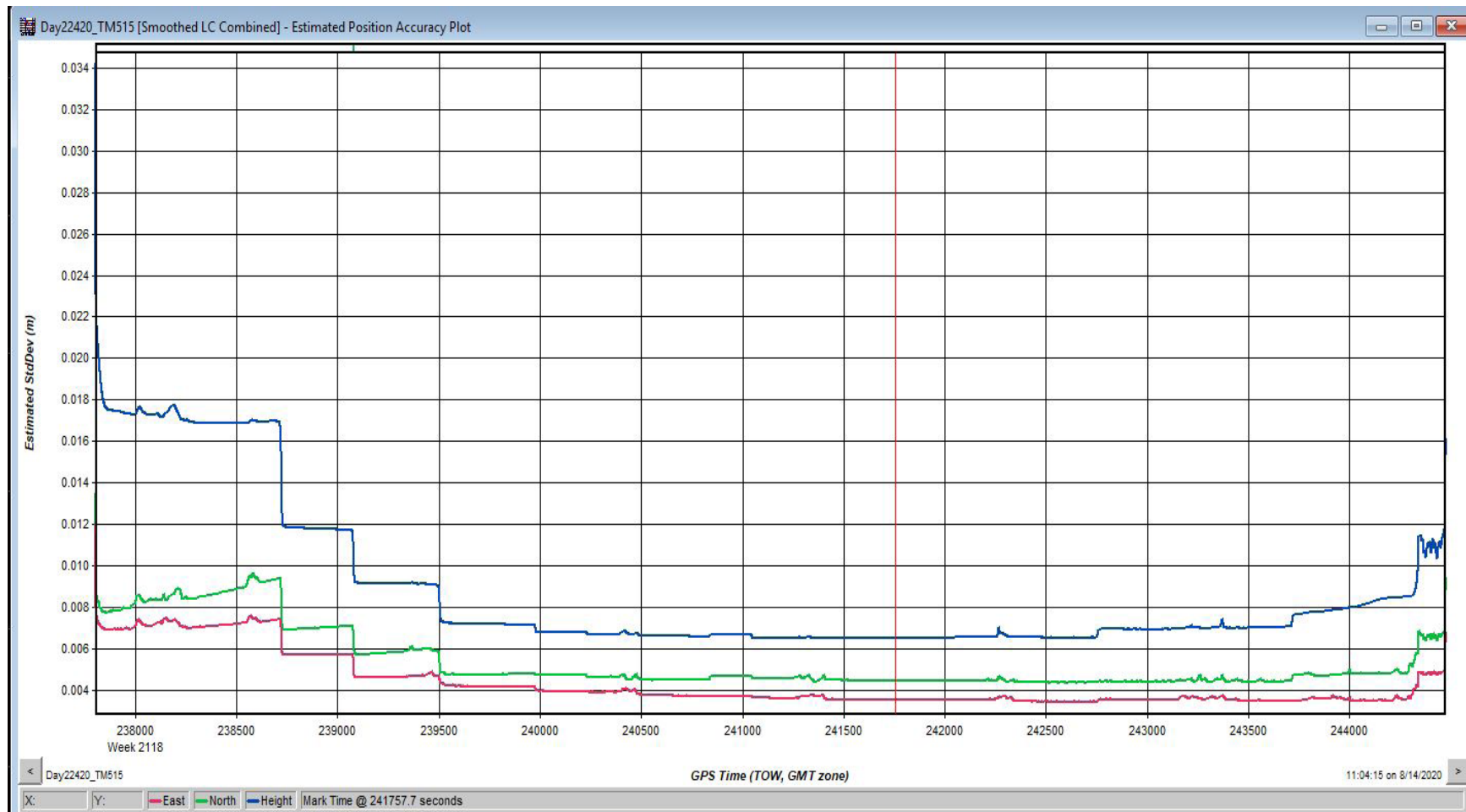
Day224420_TM515

Forward/Reverse or Combined Separation Plot



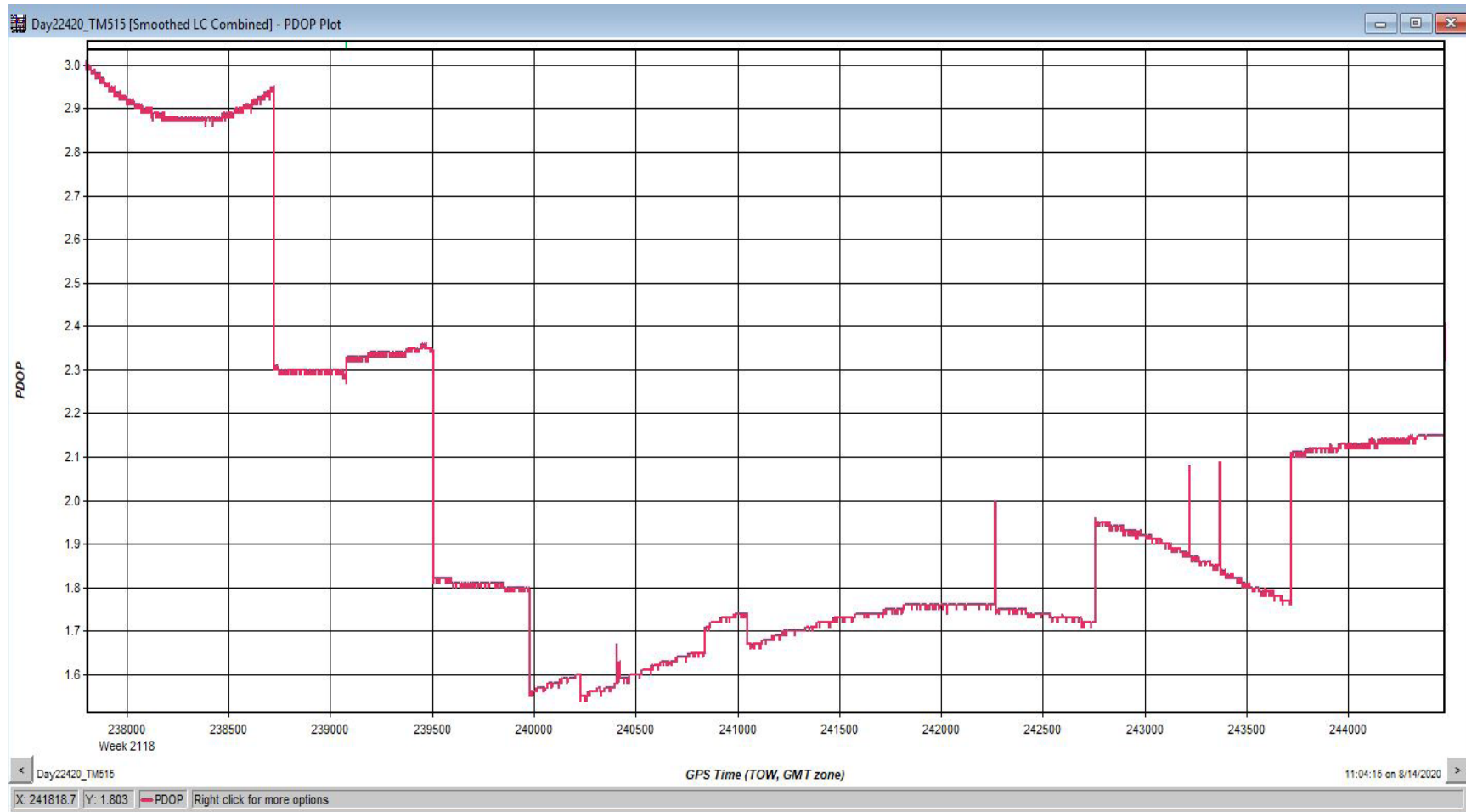
Day224420_TM515

Estimated Position Accuracy

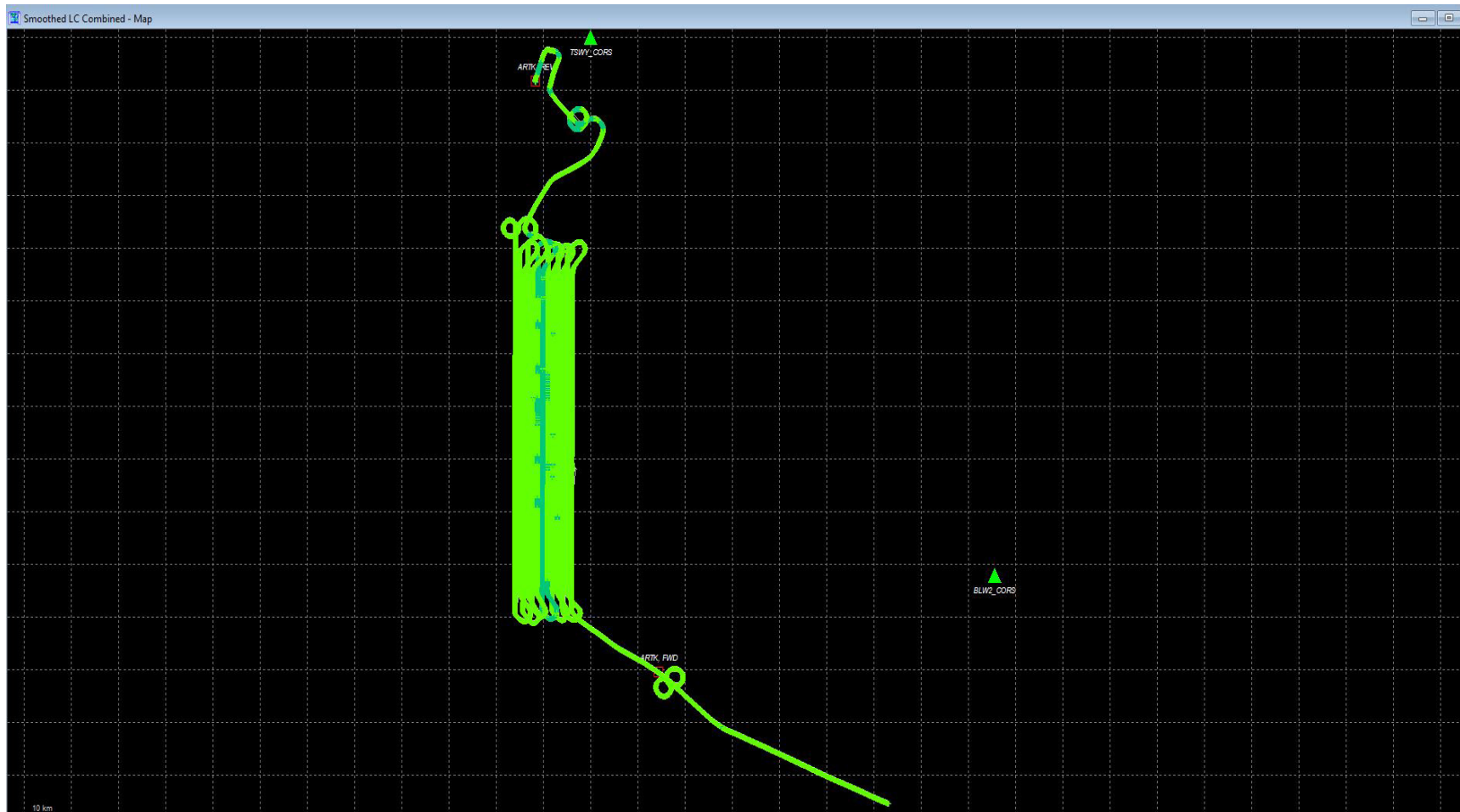


Day224420_TM515

PDOP Plot

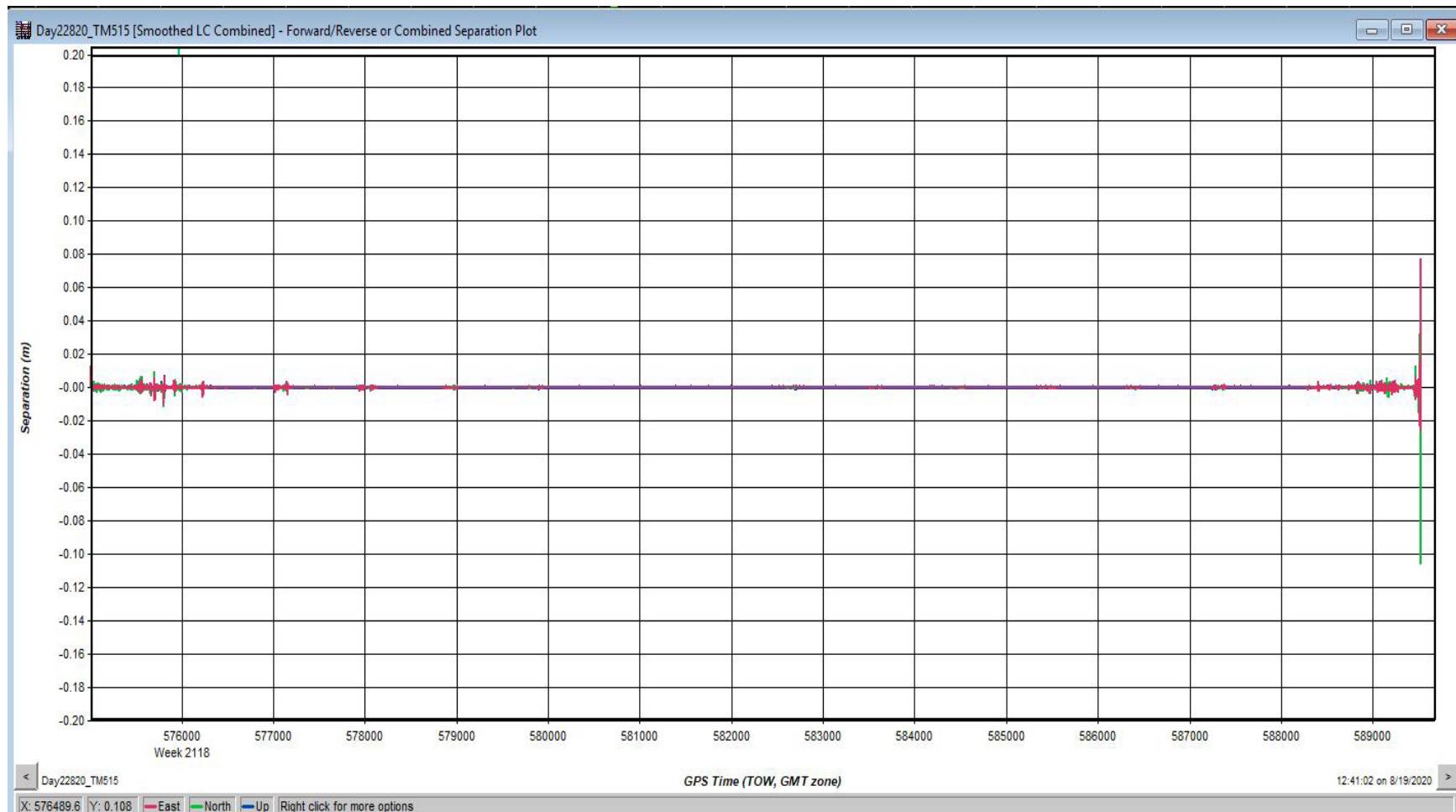


Day22820_TM515 Trajectory



Day22820_TM515

Forward/Reverse or Combined Separation Plot



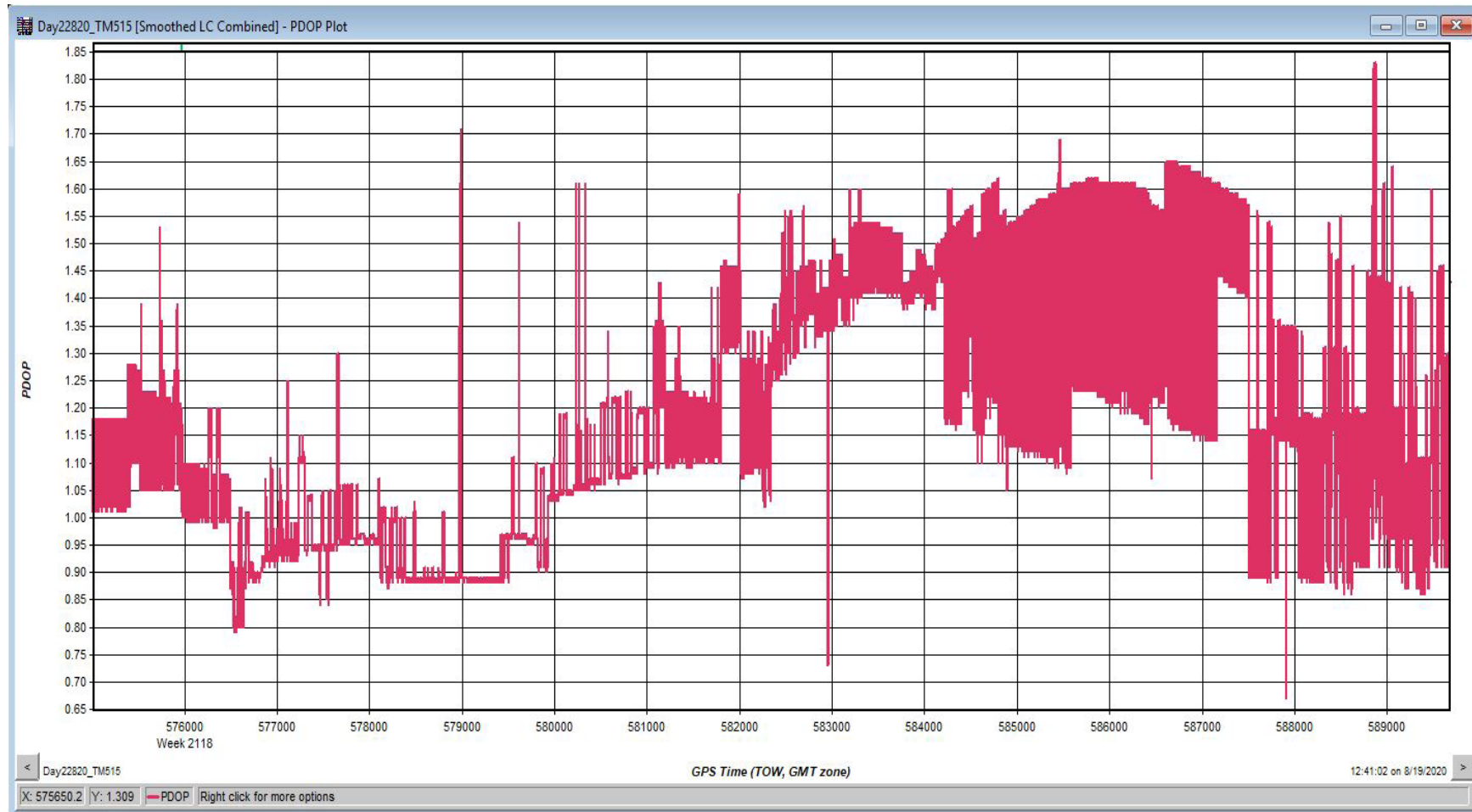
Day22820_TM515

Estimated Position Accuracy



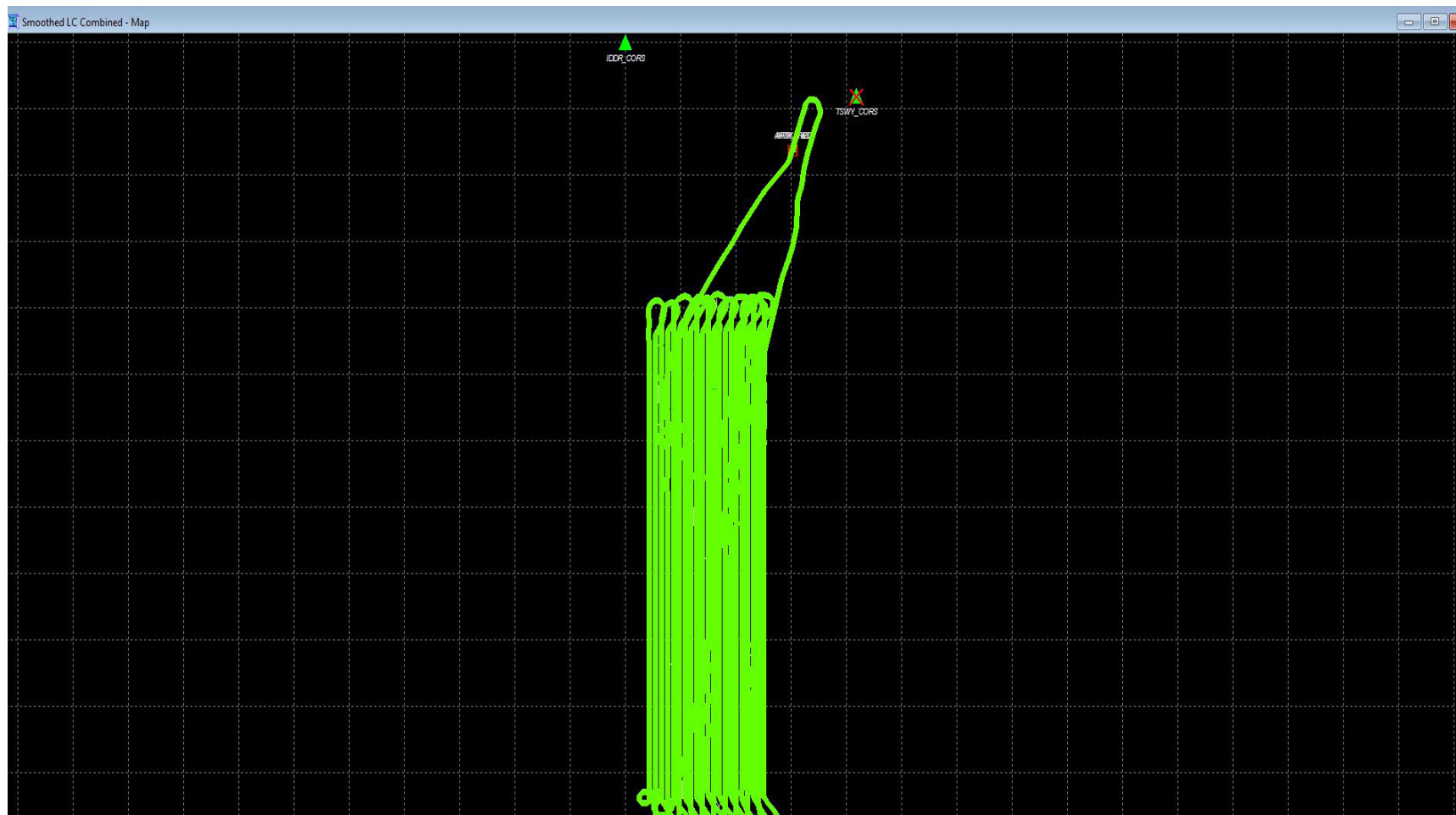
Day22820_TM515

PDOP Plot



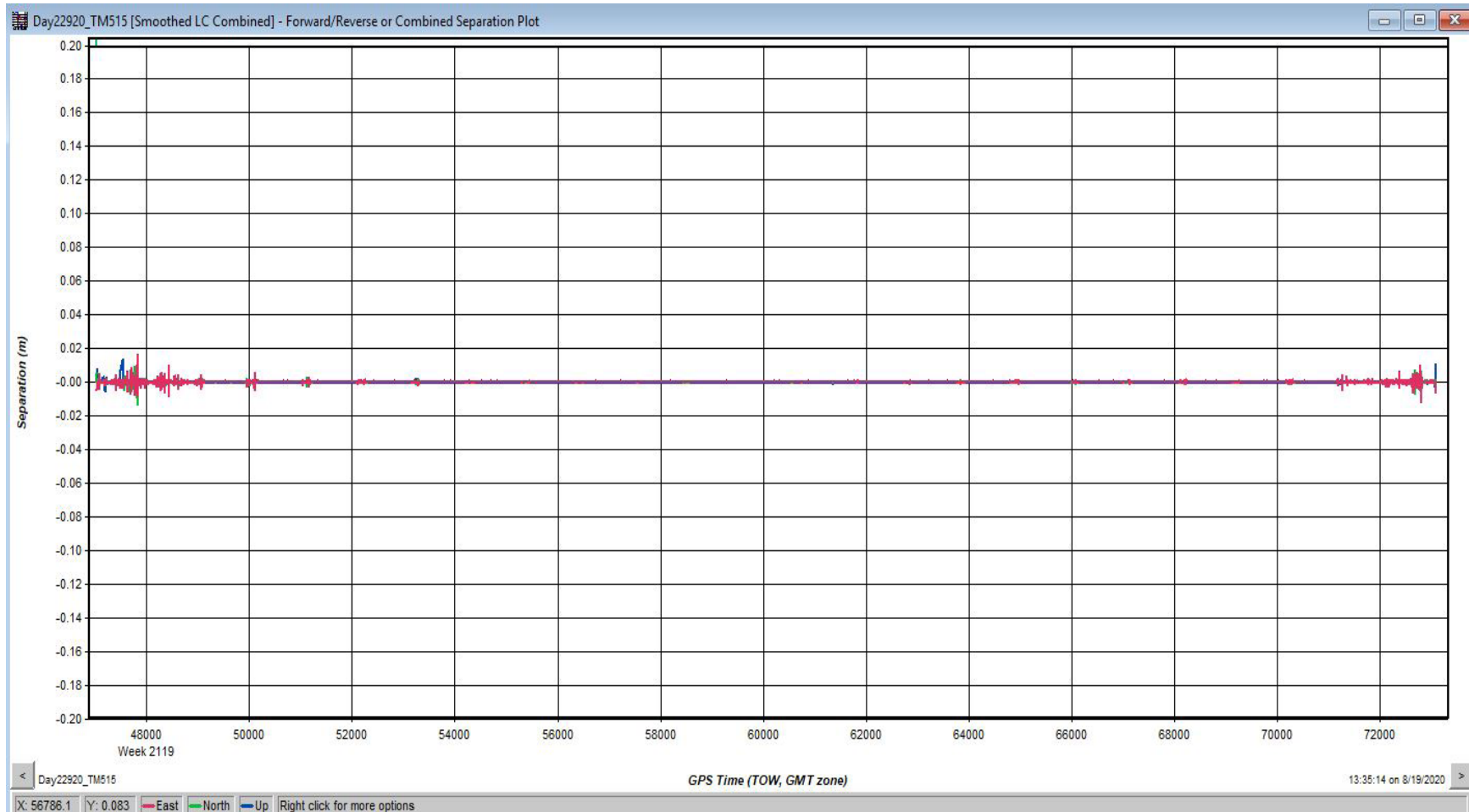
Day22920_TM515

Trajectory



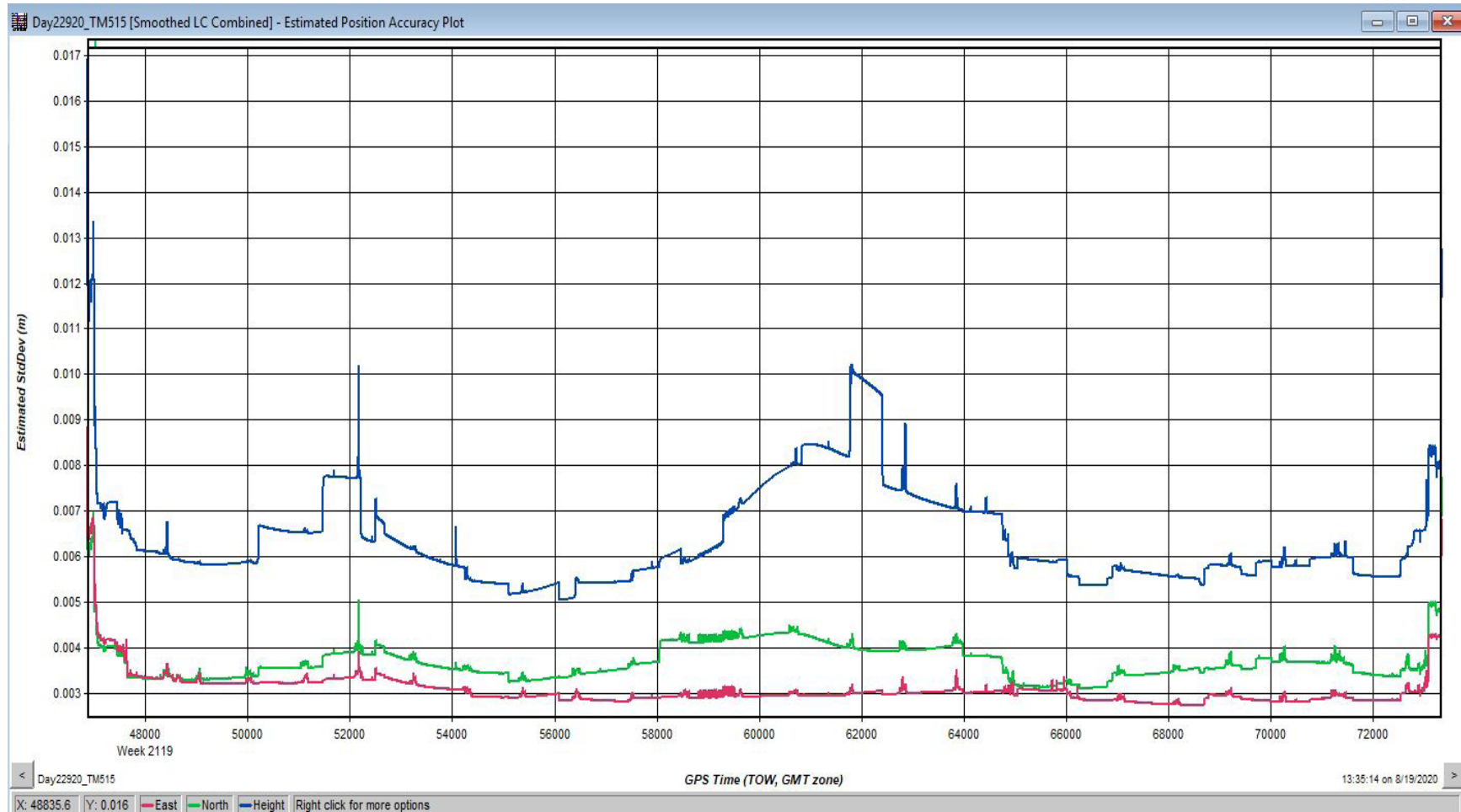
Day22920_TM515

Forward/Reverse or Combined Separation Plot



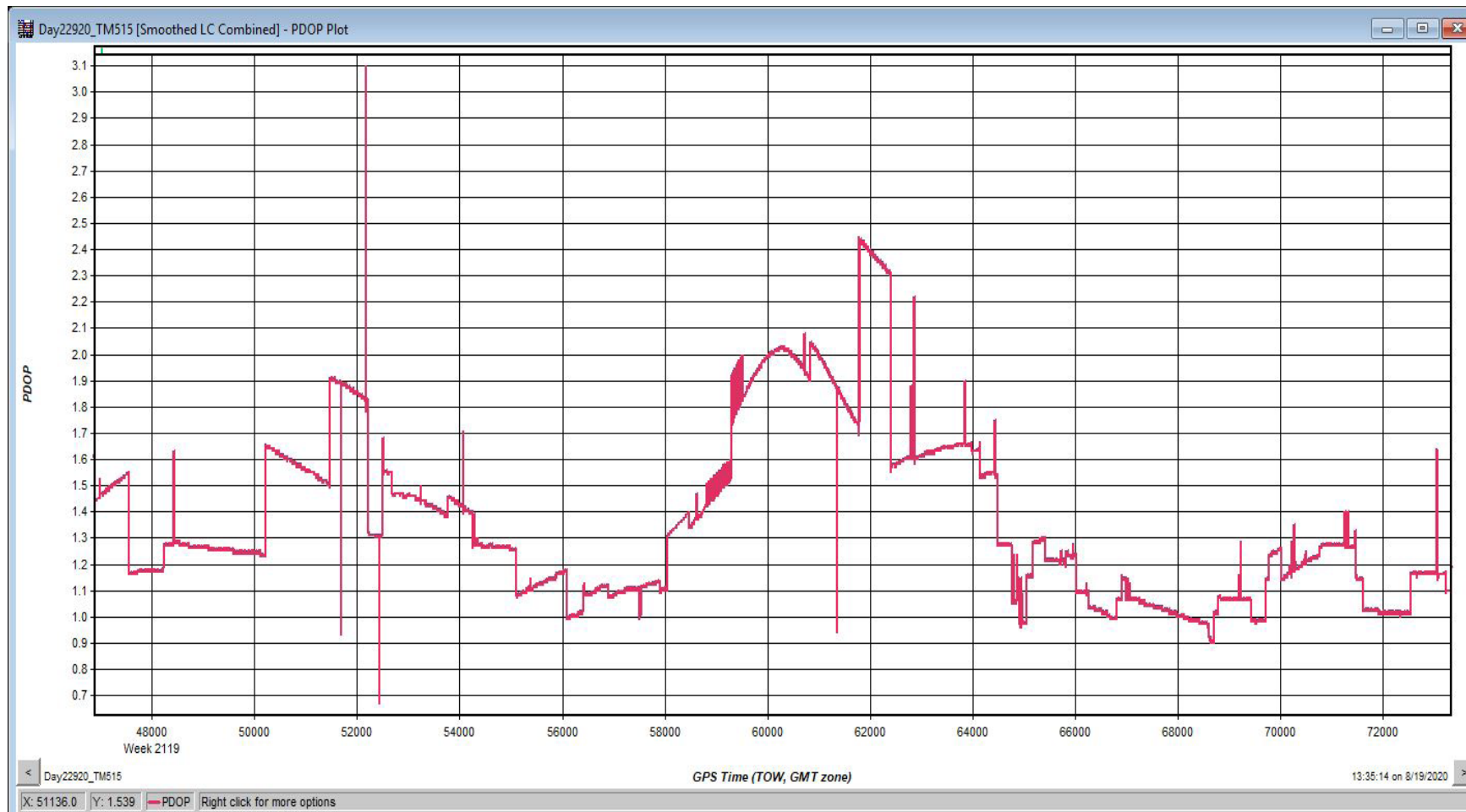
Day22920_TM515

Estimated Position Accuracy



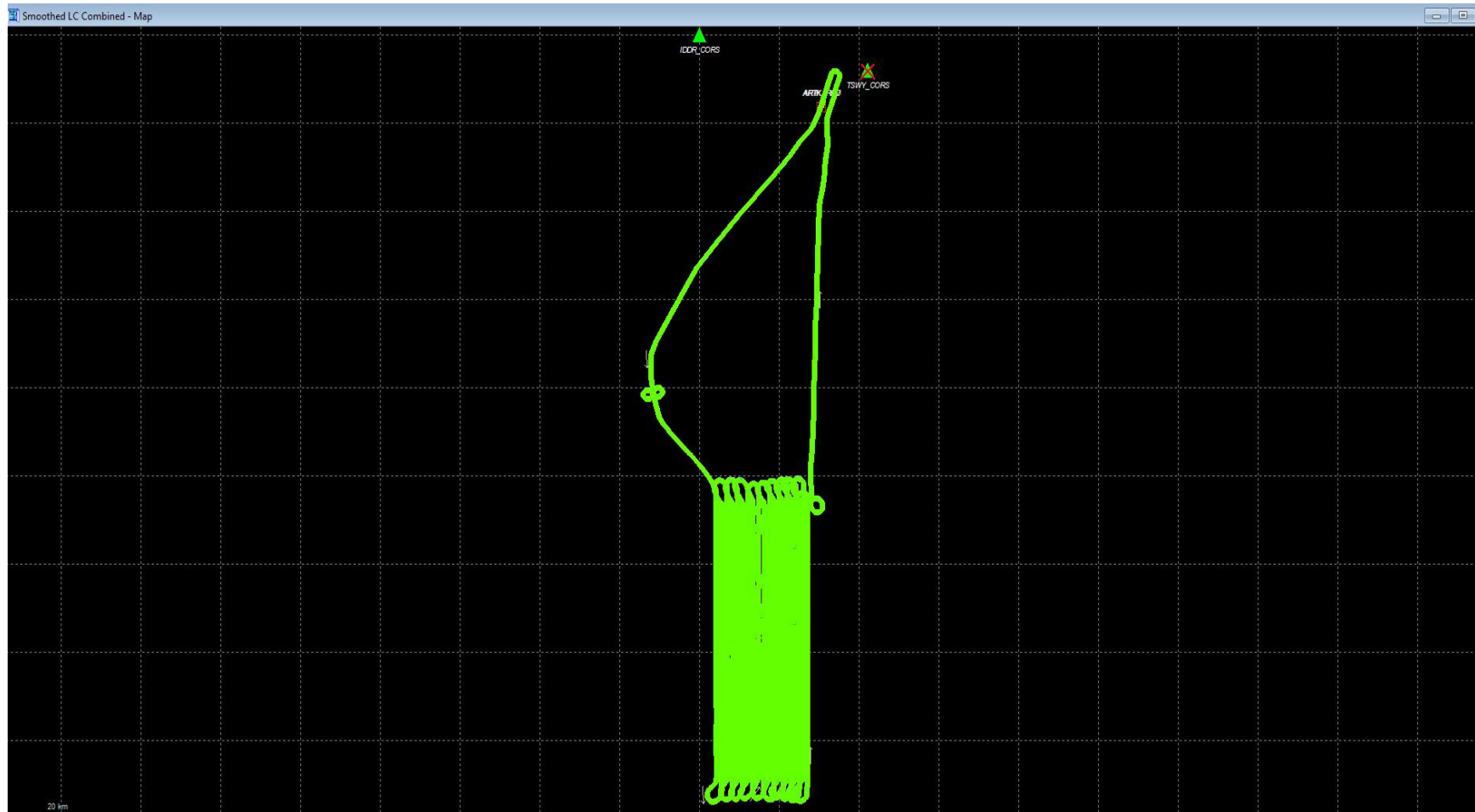
Day22920_TM515

PDOP Plot



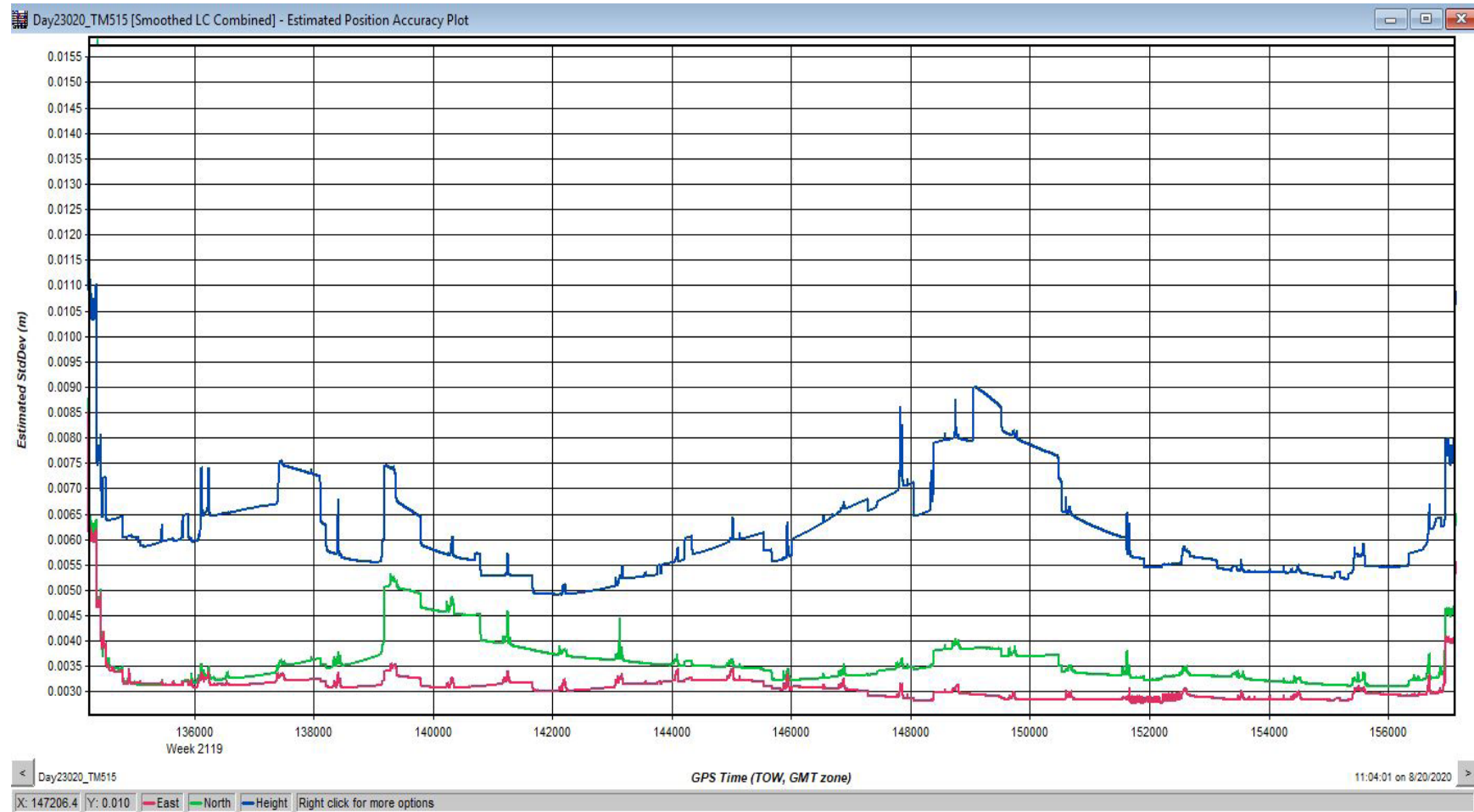
Day23020_TM515

Trajectory



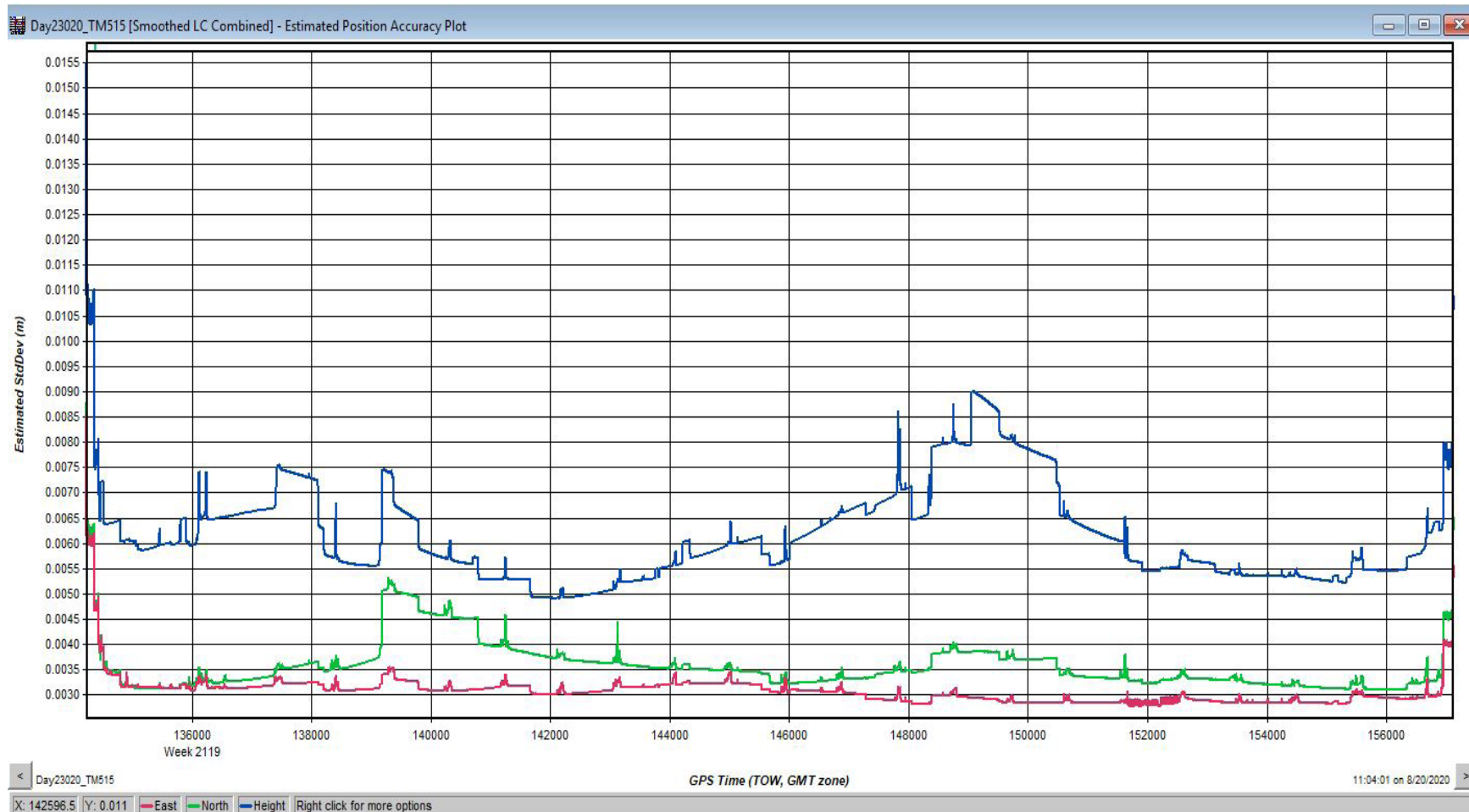
Day23020_TM515

Forward/Reverse or Combined Separation Plot



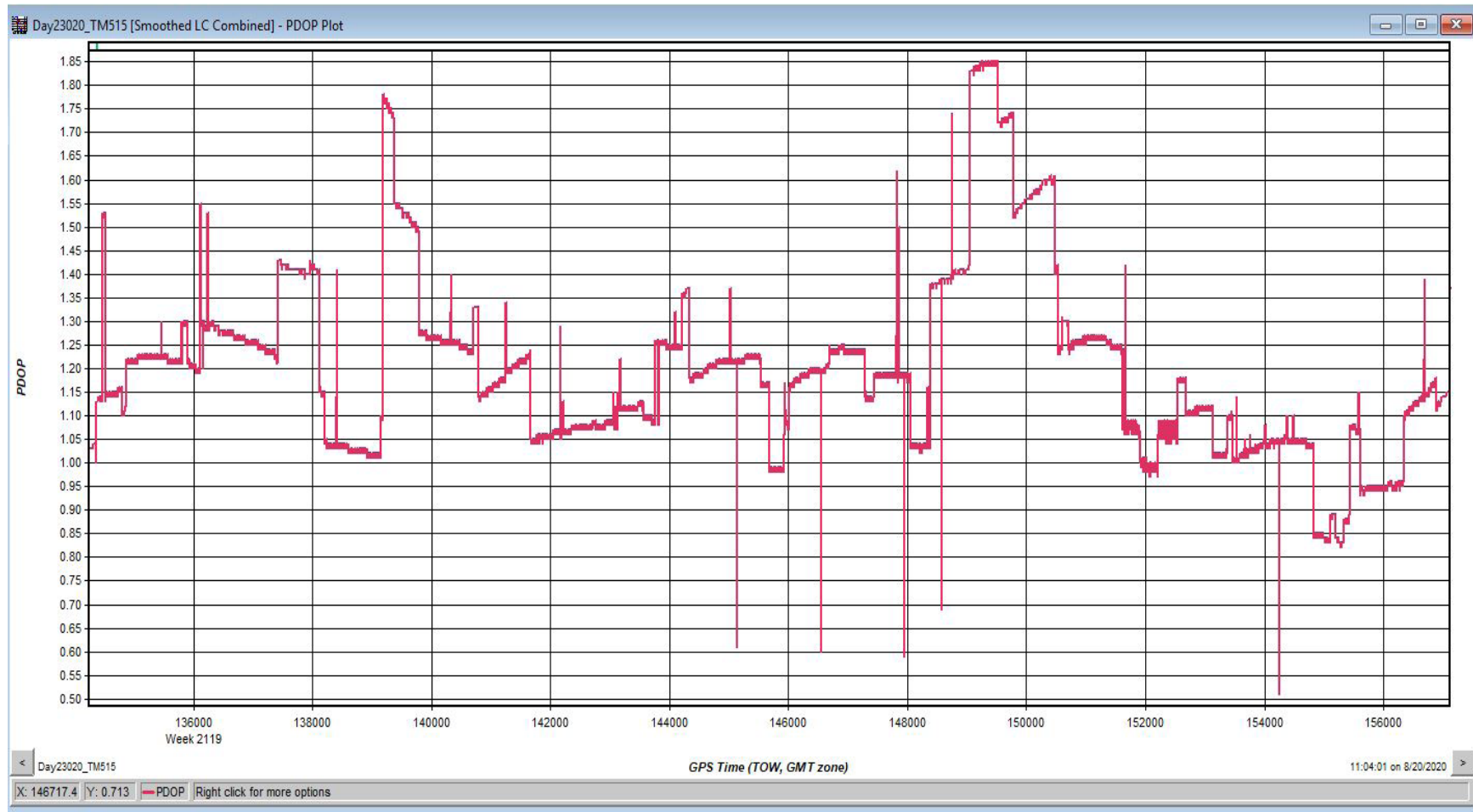
Day23020_TM515

Estimated Position Accuracy



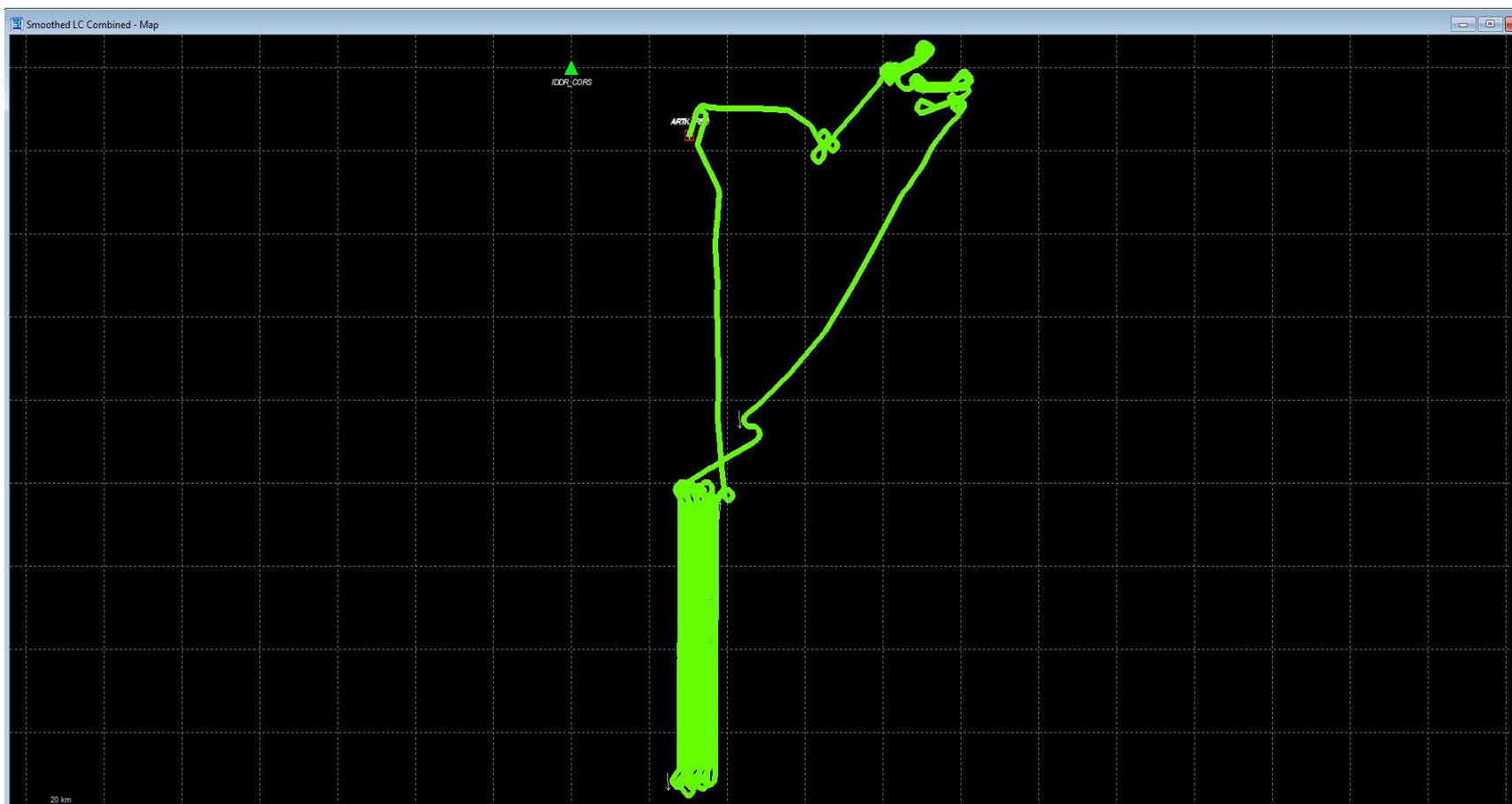
Day23020_TM515

PDOP Plot

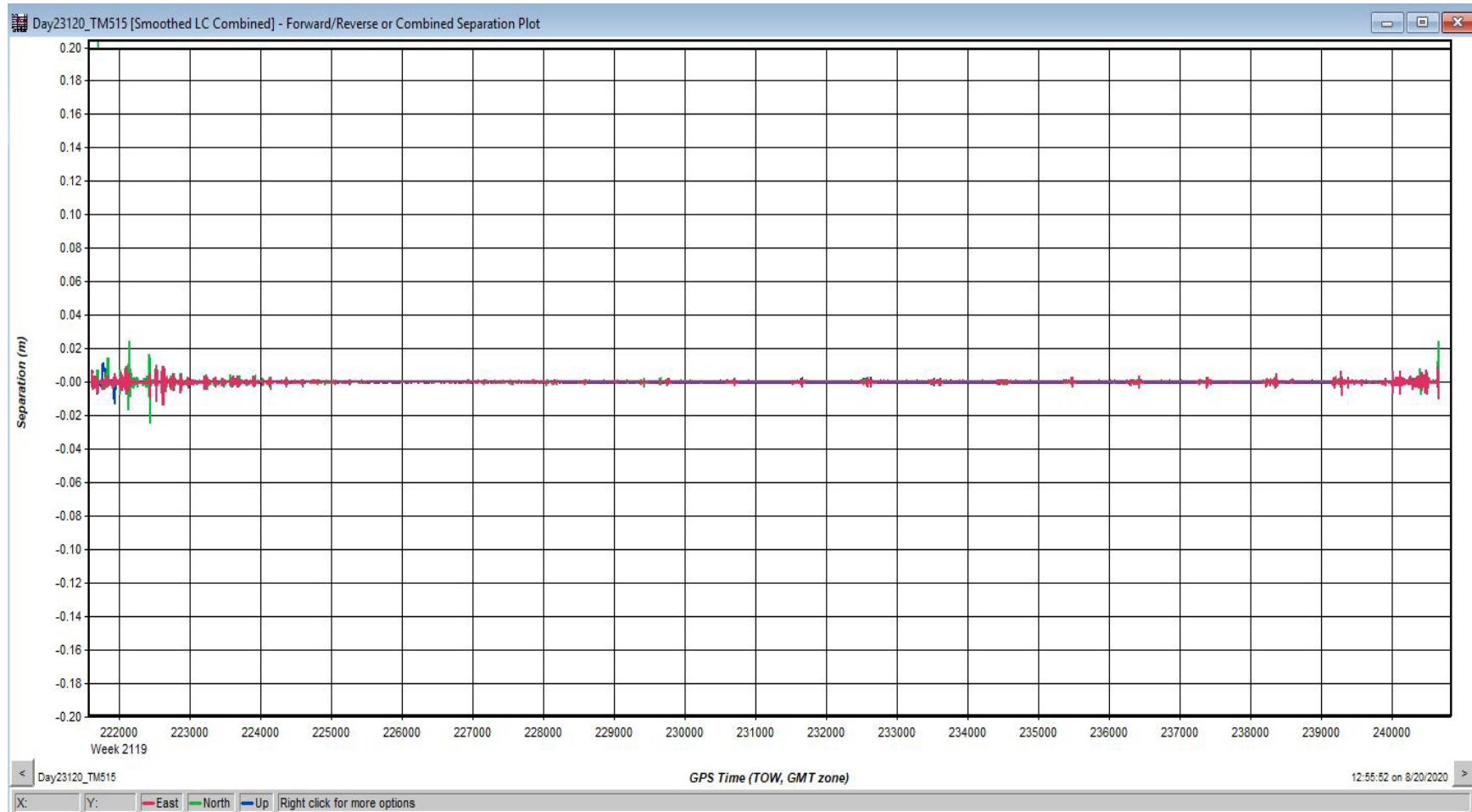


Day23120_TM515

Trajectory

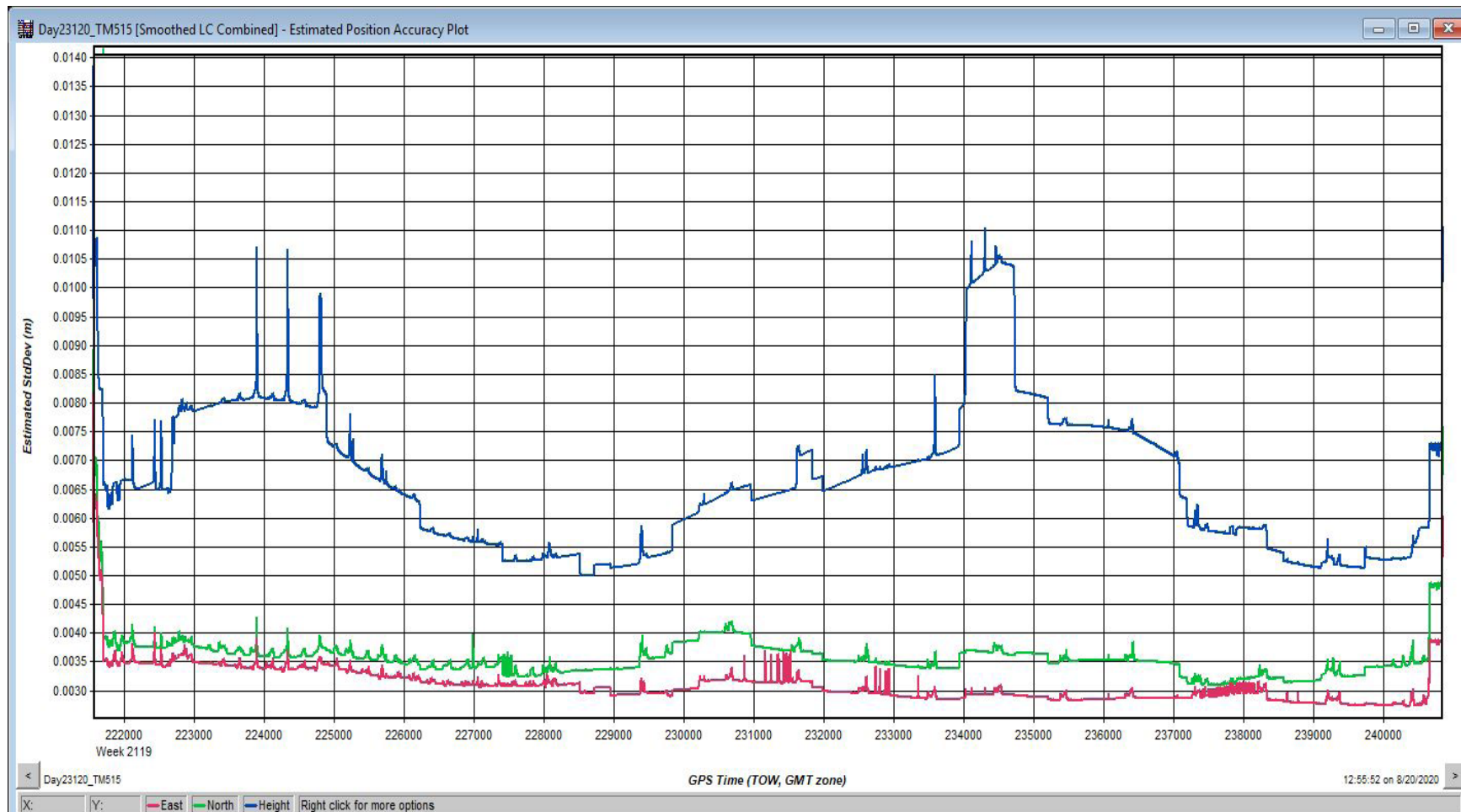


Forward/Reverse or Combined Separation Plot



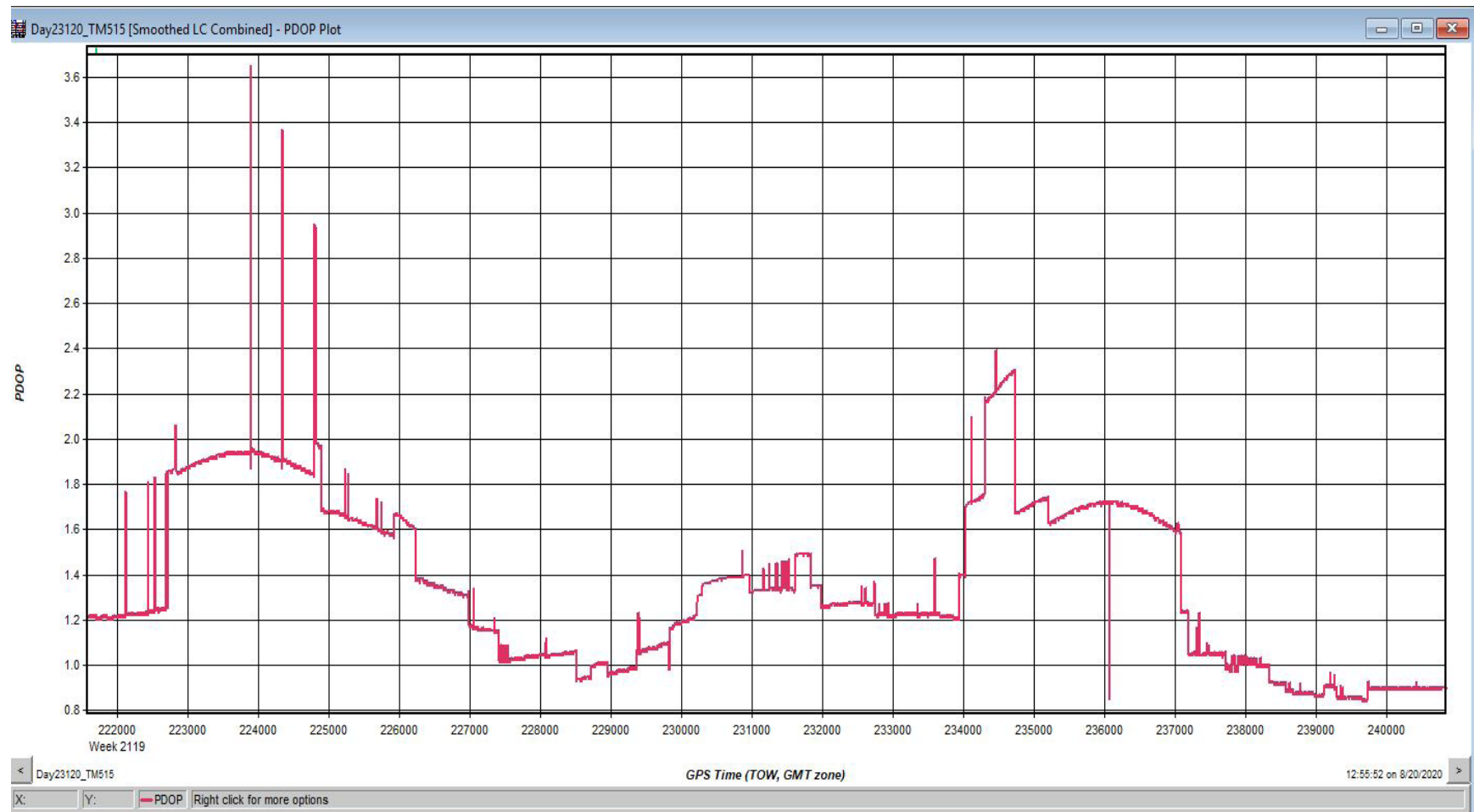
Day23120_TM515

Estimated Position Accuracy



Day23120_TM515

PDOP Plot



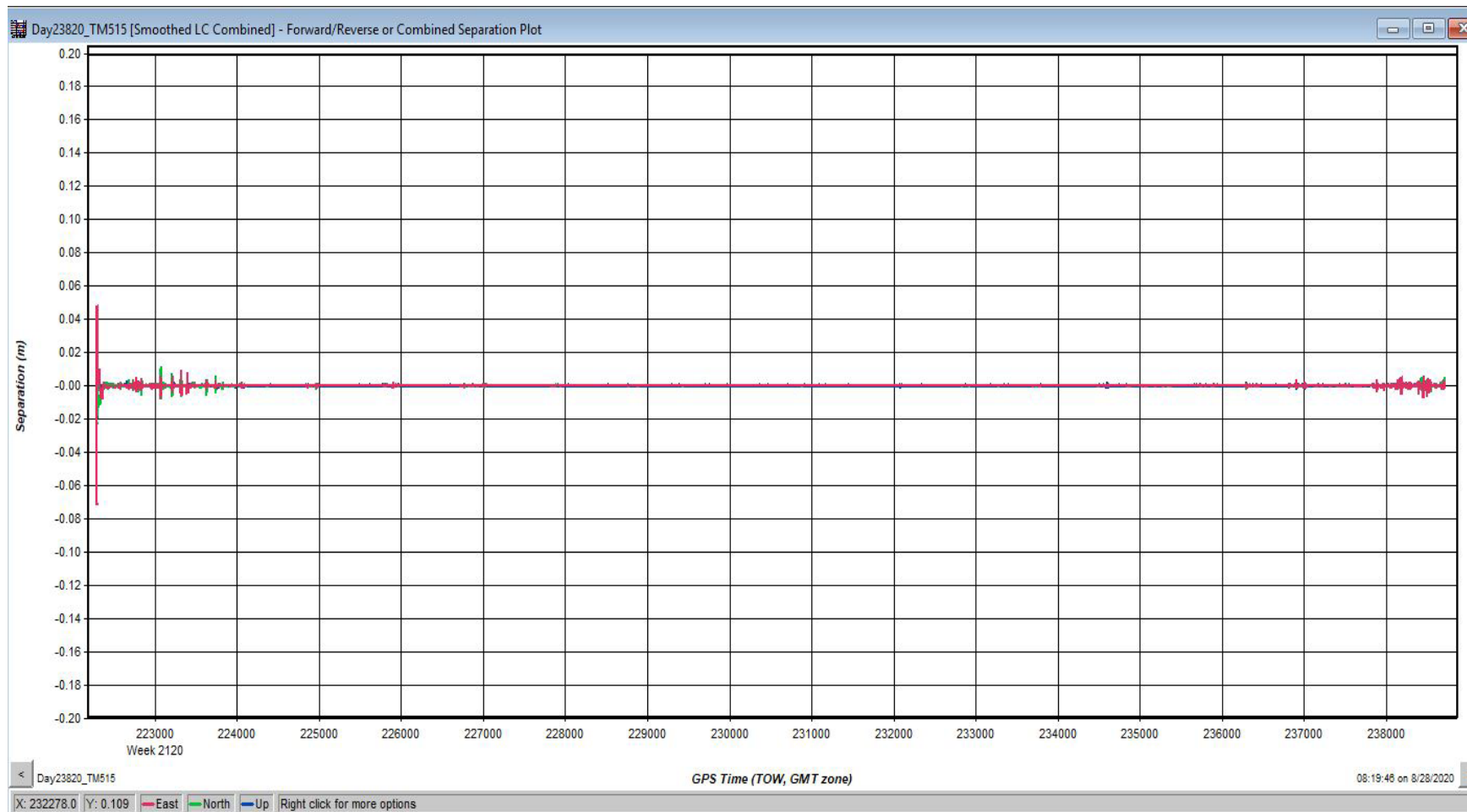
Day23820_TM515

Trajectory



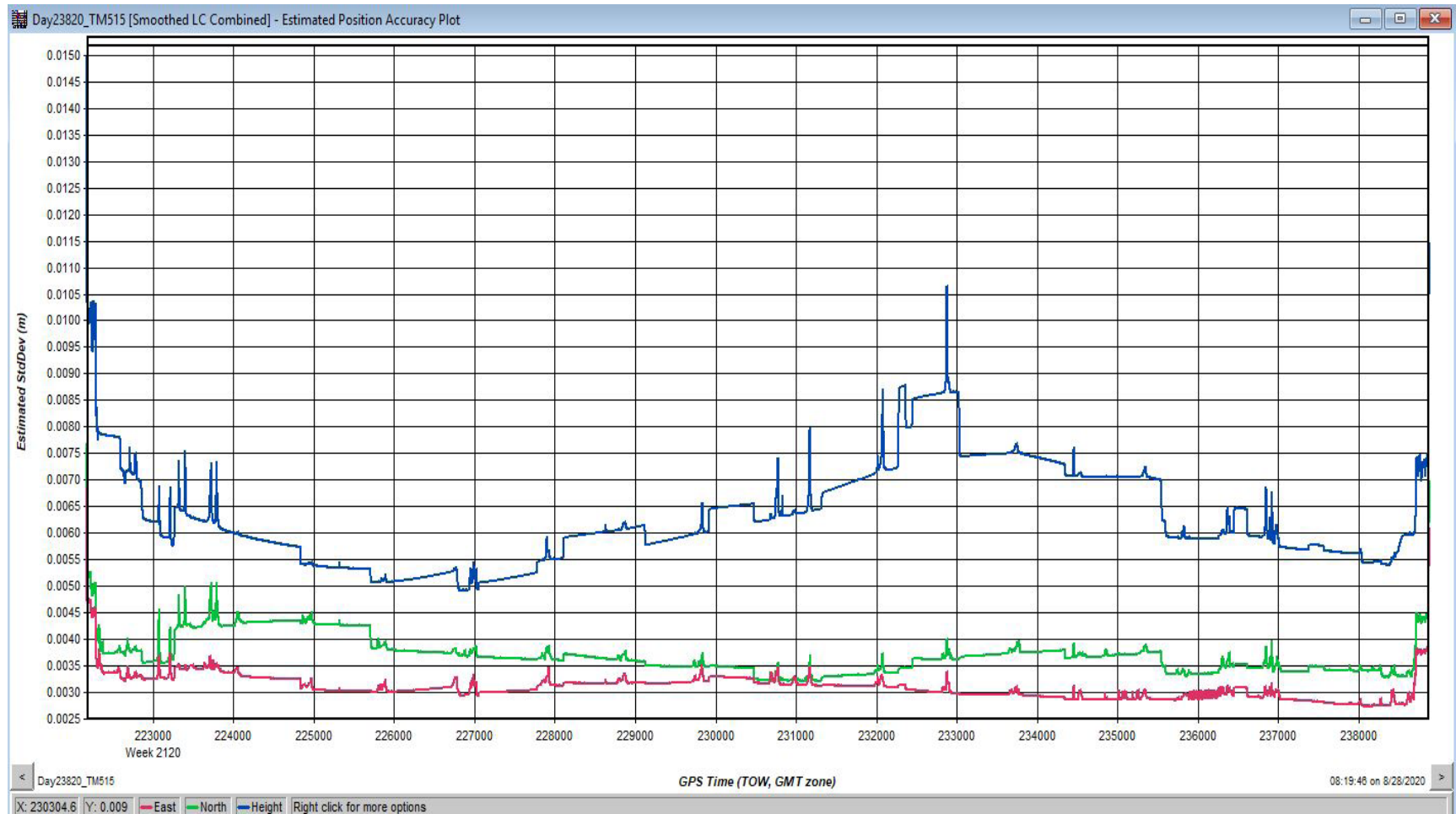
Day23820_TM515

Forward/Reverse or Combined Separation Plot



Day23820_TM515

Estimated Position Accuracy



Day23820_TM515

PDOP Plot

