Commonwealth of Puerto Rico QL2 Lidar

Report Produced for U.S. Geological Survey

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Executive Summary

Dewberry was tasked with developing a consistent and accurate topographic and bathymetric (topobathymetric) elevation dataset derived from high-accuracy Light Detection and Ranging (lidar) technology for the Commonwealth of Puerto Rico Project Area. The topobathy lidar data was acquired by the National Oceanic & Atmospheric Administration's (NOAA) National Geodetic Survey and was previously delivered to NOAA and USGS. This report specifically describes the acquisition, processing methods, assessment, and ground survey for the topographic lidar data and derivative products. For information regarding the topobathy lidar data please see Appendix E delivered with this report.

The lidar data were processed and classified according to project specifications. Detailed breaklines and bare-earth Digital Elevation Models (DEMs) were produced for the project area. Data was formatted according to tiles with each tile covering an area of 1,500 m by 1,500 m. A total of four thousand seven hundred fourteen (4,714) tiles will be produced for the project encompassing an area of approximately three thousand four hundred fifty one (3,451) square miles. The lidar data were acquired over two different acquisition campaigns. The first campaign occurred from January 26, 2016 through May 15, 2016 and acquired two thousand three hundred sixteen (2,316) square miles of topographic lidar data. The second campaign occurred from December 8, 2016 through March 16, 2017 and acquired one thousand seven hundred seventy nine (1,779) square miles of topographic lidar data. As such, the lidar data were submitted to USGS in two separate deliverables. The first deliverable contained two thousand six hundred sixty six (2,666) tiles. The second deliverable contained two thousand forty eight (2,048) tiles. Considering some of these tiles contained only water, the first deliverable contained only two thousand four hundred fifty seven (2,457) tiles of topographic data. The second deliverable contained only one thousand nine hundred ninety five (1,995) tiles of topographic data with one thousand nine hundred forty one (1,941) having ground for DEM creation. The total tile count of data tiles is four thousand four hundred forty (4,440) LAS and four thousand three hundred ninety eight (4,398) DEMs. The difference is due to some tiles only containing water points.

THE PROJECT TEAM

Dewberry served as the prime contractor for the project. In addition to project management, Dewberry was responsible for LAS classification, all lidar products, breakline production, Digital Elevation Model (DEM) production, and quality assurance.

Dewberry's Gary Simpson managed the ground survey for this project. His team surveyed accuracy assessment check points that were used for independent vertical accuracy testing of the the lidar-derived surface model. They also surveyed ground control points that were used to reference the lidar data with known ground positions. In addition, Gary verified the GPS base station coordinates used during lidar data acquisition to ensure that the base station coordinates were accurate. Please see Appendix A for the Accuracy Check Point Survey Report and Appendix B for the Ground Control Survey Report.

Leading Edge Geomatics, LLC completed lidar data acquisition and data calibration for the project area.

SURVEY AREA

The topographic lidar survey project area covers approximately three thousand four hundred fifty one (3,451) square miles of the Commonwealth of Puerto Rico which includes the outer islands of Culebra, Desecheo, Mona, Vieques, Muertos, Cabeza de Pero, and Cayo Icacos. Figure 1 shows the project boundary of the lidar survey.

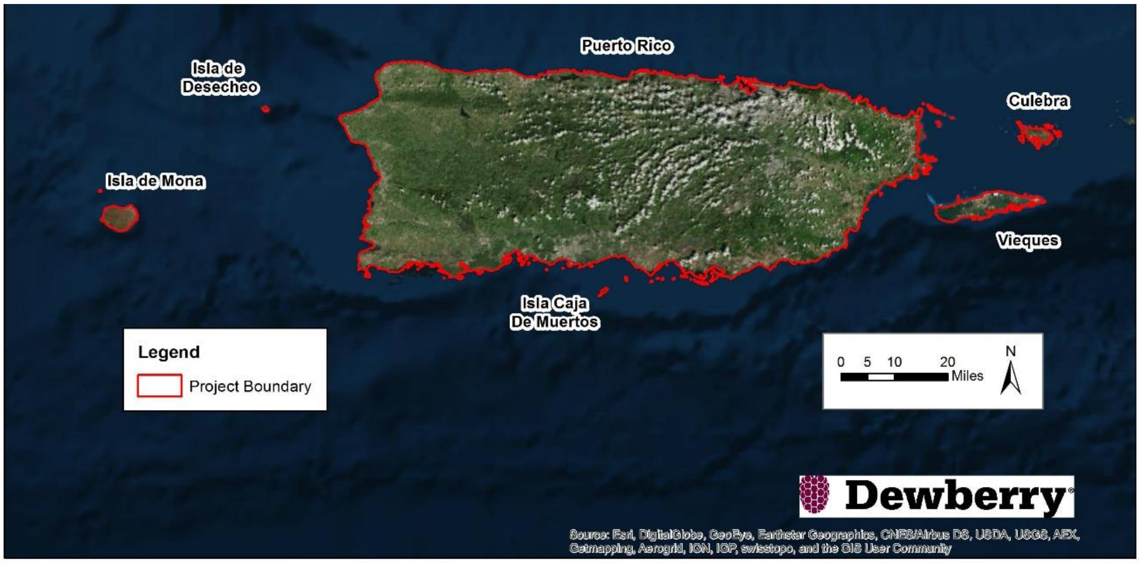


Figure 1 – Puerto Rico Topographic Lidar Project Boundary

DATE OF SURVEY

The initial lidar aerial acquisition was conducted from January 26, 2016 through May 15, 2016. However, only eighty percent (80%) of the project areas was surveyed during this acquisition period due to persistent, low lying cloud cover in the southeast region of Puerto Rico. After discussions with local officials, meteorologists, and USGS the project team determined that this cloud cover would persist through the summer and likely into the fall. Therefore, the decision was made to resume the lidar survey in December 2016 when cloud cover was expected to be less impactful. The subsequent lidar survey commenced on December 8, 2016 and was completed on March 16, 2017. Figure 2 shows the collection status of flight lines that were planned during the initial lidar acquisition.

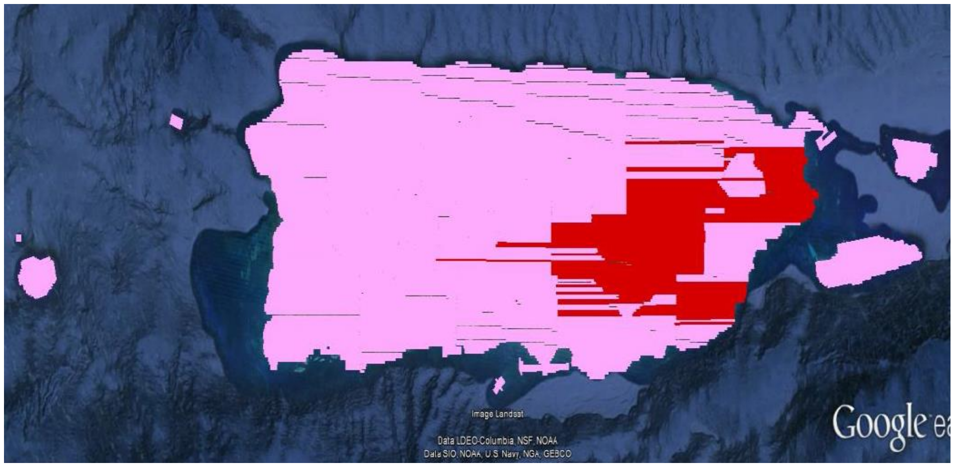


Figure 2 – Flight lines shown in pink surveyed from January 2016 to May 2016. Flight lines shown in red surveyed December 2016 to March 2017.

COORDINATE REFERENCE SYSTEM

Data produced for the project were delivered in the following reference system.

Horizontal Datum: North American Datum 1983, 2011 Adjustment (NAD83 (2011))
Vertical Datum: Puerto Rico Vertical Datum of 2002 (PRVD02)
Coordinate System: State Plane Coordinate System, Puerto Rico Zone 5200
Units: Horizontal units are in meters, Vertical units are in meters.
Geiod Model: Geoid12B (Geoid 12B was used to convert ellipsoid heights to orthometric heights).

LIDAR VERTICAL ACCURACY

For the Puerto Rico QL2 Lidar Project, the tested $RMSE_z$ of the classified lidar data for checkpoints in non-vegetated terrain equaled **9.3 cm** compared with the 10 cm specification; and the NVA of the classified lidar data computed using $RMSE_z$ x 1.9600 was equal to **18.2 cm**, compared with the 19.6 cm specification.

For the Puerto Rico Topographic Lidar Project, the tested VVA of the classified lidar data computed using the 95^{th} percentile was equal to **20.6 cm,** compared with the 29.4 cm specification.

Additional accuracy information and statistics for the classified lidar data, raw swath data, and bare earth DEM data are found in the following sections of this report.

PROJECT DELIVERABLES

The deliverables for the project are listed below.

1. Raw Point Cloud Data (Swaths)
2. Classified Point Cloud Data (Tiled)
3. Bare Earth Surface (Raster DEM – IMG Format)
4. Intensity Images (8-bit gray scale, tiled, GeoTIFF format)
5. Breakline Data (File GDB)
6. Independent Survey Checkpoint Data (Report, Photos, & Points)
7. Calibration Points
8. Metadata

9. Project Report (Acquisition, Processing, QC)
10. Project Extents, Including a shapefile derived from the lidar deliverable.

PROJECT TILING FOOTPRINT

The first deliverable contained two thousand six hundred and sixty six (2,666) tiles. The second deliverable contained two thousand forty eight (2,048) tiles. The total tile count is four thousand seven hundred fourteen (4,714). Considering some of these tiles contained only water, the first deliverable contained only two thousand four hundred and fifty seven tiles (2,457) tiles of actual data. The second deliverable contained only one thousand nine hundred ninety five (1,995) tiles of actual data. The total tile count of actual data tiles is four thousand four hundred fifty two (4,452). The tile grid in Figure 3 is based on the U.S. National Grid and each tile's extent is 1,500 meters by 1,500 meters (see Appendix B for a complete listing of delivered tiles).

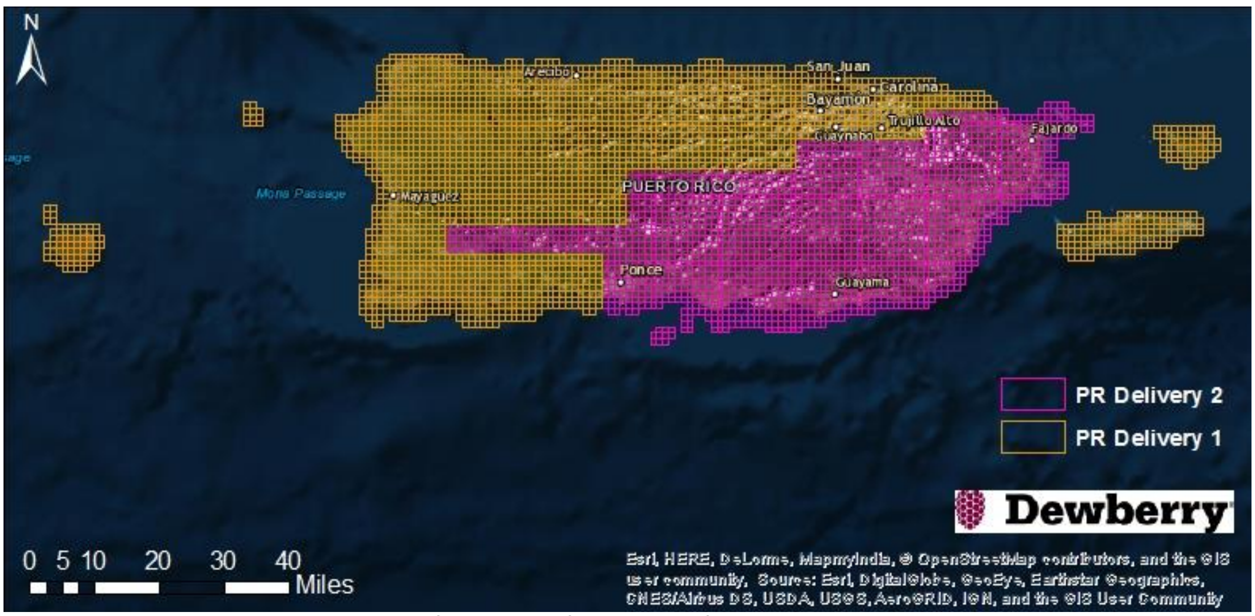


Figure 3 – Lidar Data Tile Scheme

Lidar Acquisition Report

Dewberry elected to subcontract the lidar acquisition and calibration activities to Leading Edge Geomatics (LEG). LEG was responsible for providing lidar acquisition, calibration and delivery of lidar data files to Dewberry.

Dewberry received calibrated swath data from LEG on April 4, 2016 and August 2, 2016.

LIDAR ACQUISITION DETAILS

LEG planned two thousand two hundred forty two (2,242) passes for the project area as a series of parallel flight lines with cross flight lines for the purposes of quality control. The flight plan included zigzag flight line collection as a result of the inherent IMU drift associated with all IMU systems. Due to large changes in terrain height, the project area was broken down into three areas based on height above sea level. This was required to maintain the project accuracy specification. In order to reduce any margin for error in the flight plan, LEG followed FEMA's Appendix A "guidelines" for flight planning and, at a minimum, includes the following criteria:

- A digital flight line layout using Track Air flight design software for direct integration into the aircraft flight navigation system.
- Planned flight lines; flight line numbers; and coverage area.
- Lidar coverage extended by a predetermined margin beyond all project borders to ensure necessary over-edge coverage appropriate for specific task order deliverables.
- Local restrictions related to air space and any controlled areas have been investigated so that required permissions can be obtained in a timely manner with respect to schedule. Additionally, LEG will file our flight plans as required by local Air Traffic Control (ATC) prior to each mission.

LEG monitored weather and atmospheric conditions and conducted lidar missions only when no conditions exist below the sensor that will affect the collection of data. These conditions include leaf-off for hardwoods, no snow, rain, fog, smoke, mist and low clouds. Lidar systems are active sensors, not requiring light, thus missions may be conducted during night hours when weather restrictions do not prevent collection. LEG accesses reliable weather sites and indicators (webcams) to establish the highest probability for successful collection in order to position our sensor to maximize successful data acquisition.

Within 72-hours prior to the planned day(s) of acquisition, LEG closely monitored the weather, checking all sources for forecasts at least twice daily. As soon as weather conditions were conducive to acquisition, our aircraft mobilized to the project site to begin data collection. Once on site, the acquisition team took responsibility for weather analysis.

Leading Edge Geomatics lidar sensors are calibrated at a designated site located in downtown Fredericton, New Brunswick and are periodically checked and adjusted to minimize corrections at project sites. Both systems were calibrated before departing for the project area. Leading Edge Geomatics also completed a calibration over San Juan for calibration verification.

LIDAR SYSTEM PARAMETERS

Leading Edge Geomatics operated two Cessna 172 (C-FMNB, C-FCAU) and a Piper Navajo (C-GKCN). Each of the Cessna's carried a Riegl 680i scanner and the Navajo carried a Riegl 780. Table 1 illustrates Leading Edge Geomatics system parameters for lidar acquisition on this project.

Item	Parameter	
System	Riegl 680i	Riegl 780
Altitude (AGL meters)	1100	900
Approx. Flight Speed (knots)	100	120
Scanner Pulse Rate (kHz)	200	200
Scan Frequency	2358	4715
Pulse Duration of the Scanner (nanoseconds)	5	5
Pulse Width of the Scanner (m)	1.5	1.5
Swath width (m)	291	291
Central Wavelength of the Sensor Laser (nanometers)	1064	1064
Did the Sensor Operate with Multiple Pulses in The Air? (yes/no)	No	No
Beam Divergence (milliradians)	0.5	0.25
Nominal Swath Width on the Ground (m)	1270	1039
Swath Overlap (%)	50	50
Total Sensor Scan Angle (degree)	60	60
Computed Down Track spacing (m) per beam	0.7	0.63
Computed Cross Track Spacing (m) per beam	0.7	0.63
Nominal Pulse Spacing (single swath), (m)	0.7	0.65
Nominal Pulse Density (single swath) (ppsm), (m)	2.059	2.487
Aggregate NPS (m) (if ANPS was designed to be met through single coverage, ANPS and NPS will be equal)	0.5	0.456
Aggregate NPD (m) (if ANPD was designed to be met through single coverage, ANPD and NPD will be equal)	4	4.8
Maximum Number of Returns per Pulse	unlimited	unlimited

Table 1: Leading Edge Geomatics lidar system parameters

ACQUISITION STATUS REPORT AND FLIGHTLINES

Upon notification to proceed, the flight crew loaded the flight plans and validated the flight parameters. The Acquisition Manager contacted air traffic control and coordinated flight pattern requirements. Lidar acquisition began immediately upon notification that control base stations were in place. During flight operations, the flight crew monitored weather and atmospheric conditions. Lidar missions were flown only when no condition existed below the sensor that would affect the collection of data. The pilot constantly monitored the aircraft course, position, pitch, roll, and yaw of the aircraft. The sensor operator monitored the sensor, the status of PDOPs, and performed the first Q/C review during acquisition. The flight crew constantly reviewed weather, water conditions and cloud locations. Any flight lines impacted by unfavorable conditions were marked as invalid and re-flown immediately or at an optimal time. Figure 4 shows the combined trajectory of the flightlines.

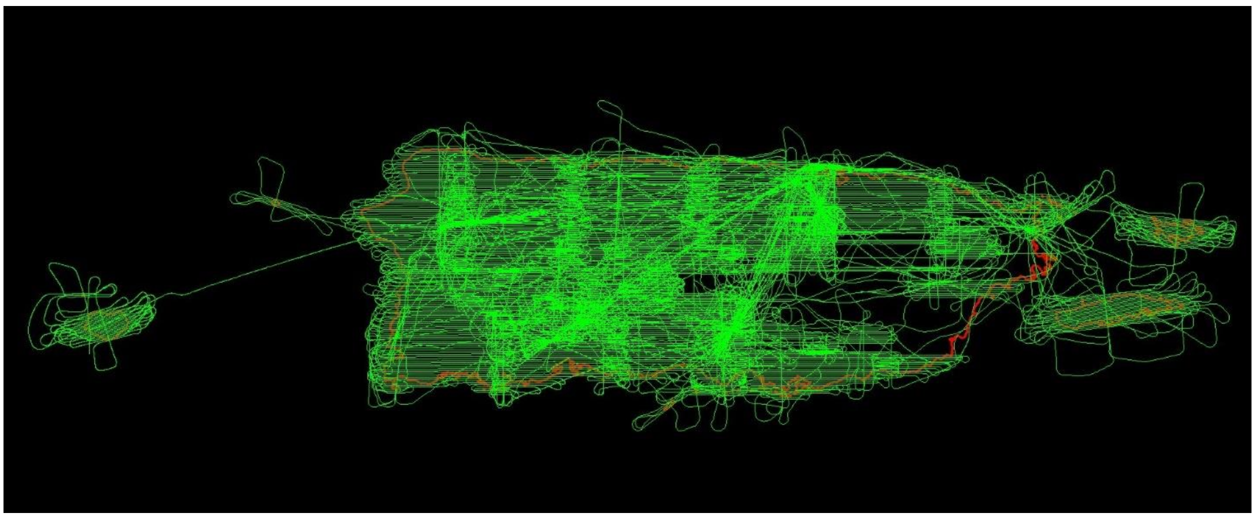


Figure 4: Trajectories as flown by Leading Edge Geomatics.

LIDAR CONTROL

Ten CORS base stations listed in Table 2 were employed by Leading Edge Geomatics for the collection. All stations coordinates were the published CORS (2011). The coordinates of all used base stations are provided in the table below. All control and calibration points are also provided in shapefile format as part of the final deliverables.

Name	NAD83 (2011) Puerto Rico State Plane		Ellipsoid Ht (NAD83 (2011), m)	Orthometric Ht (PRVD02 Geoid12B, m)
	Easting X (m)	Northing Y (m)		
PRAR	177385.0822	268319.5488	-18.543	24.9412
PRGY	159651.0549	224127.6493	35.76	75.2273
PRHL	229565.292	260531.3419	-22.539	18.8358
PRJC	140157.4015	256417.8022	24.727	66.4938
PRLP	259777.1193	240110.3683	58.883	98.7046
PRFJ	282657.2547	254740.455	-20.768	20.6545
PRLT	119984.3796	225234.2837	-13.36	26.7868
PRN4	206801.2228	227146.0813	131.067	169.7802
VITH	354752.3682	257065.5267	6.38	48.5751

CRO1	396088.4633	192529.7392	-29.423	11.8903

Table 2 – Base stations used to control lidar acquisition

AIRBORNE GPS KINEMATIC

Airborne GPS data was processed using the PosPac kinematic On-The-Fly (OTF) software suite. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 40 km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3 cm average or better but no larger than 10 cm being recorded.

GPS processing reports for each mission are included in Appendix C.

GENERATION AND CALIBRATION OF LASER POINTS (RAW DATA)

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Subsequently the mission points are output using Riegl's RiProcess application. System calibration was conducted prior to the aircraft departing for the project and the initial calibration values are used to position the point cloud. If a calibration error greater than specification is observed within the mission, the roll, pitch and yaw corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

Data collected by the lidar unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

On a project level, a supplementary coverage check is carried out to ensure no data voids unreported by Field Operations are present. The results of this check are shown in Figure 5.

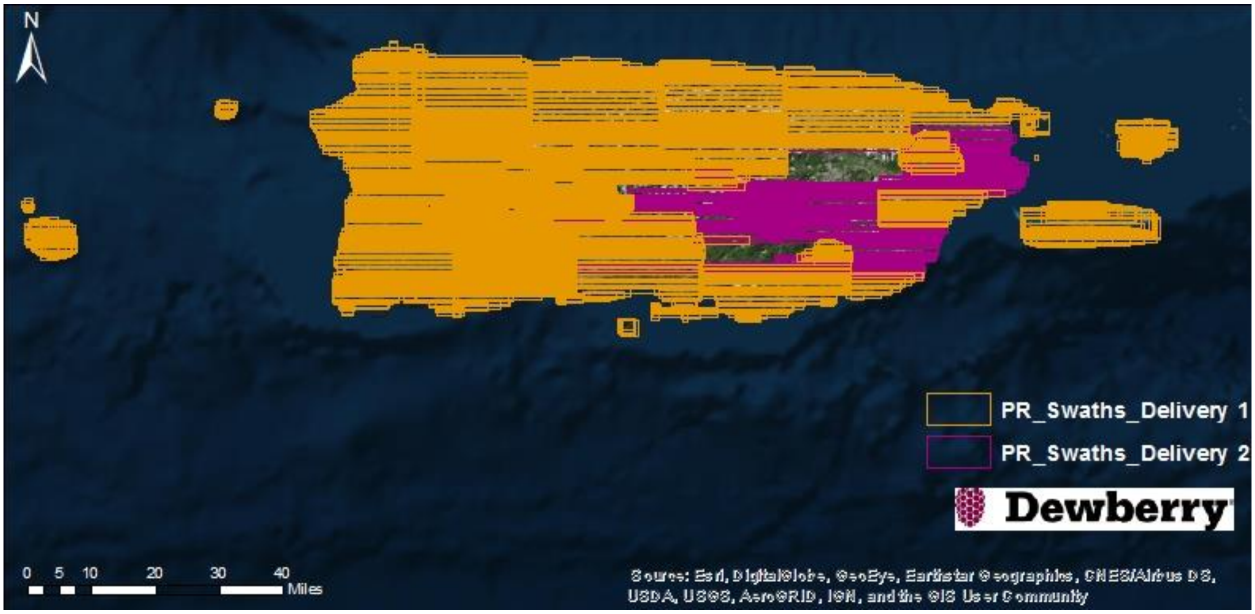


Figure 5 – Lidar swath output showing coverage.

BORESIGHT AND RELATIVE ACCURACY

The initial points for each mission calibration are inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the lidar unit or GPS. Roll, pitch and scanner scale are optimized during the calibration process until the relative accuracy is met.

Relative accuracy and internal quality are checked using at least 3 regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flight line to flight line and mission to mission agreement.

For this project the specifications used are as follows:

Absolute Vertical Accuracy <=10 cm RMSEz in non-vegetated open areas.
Absolute Horizontal Accuracy = 0.6 m RMSEr
Relative Swath Accuracy ≤ 6 cm and ≤ 8 cm RMSDz within swath overlap.

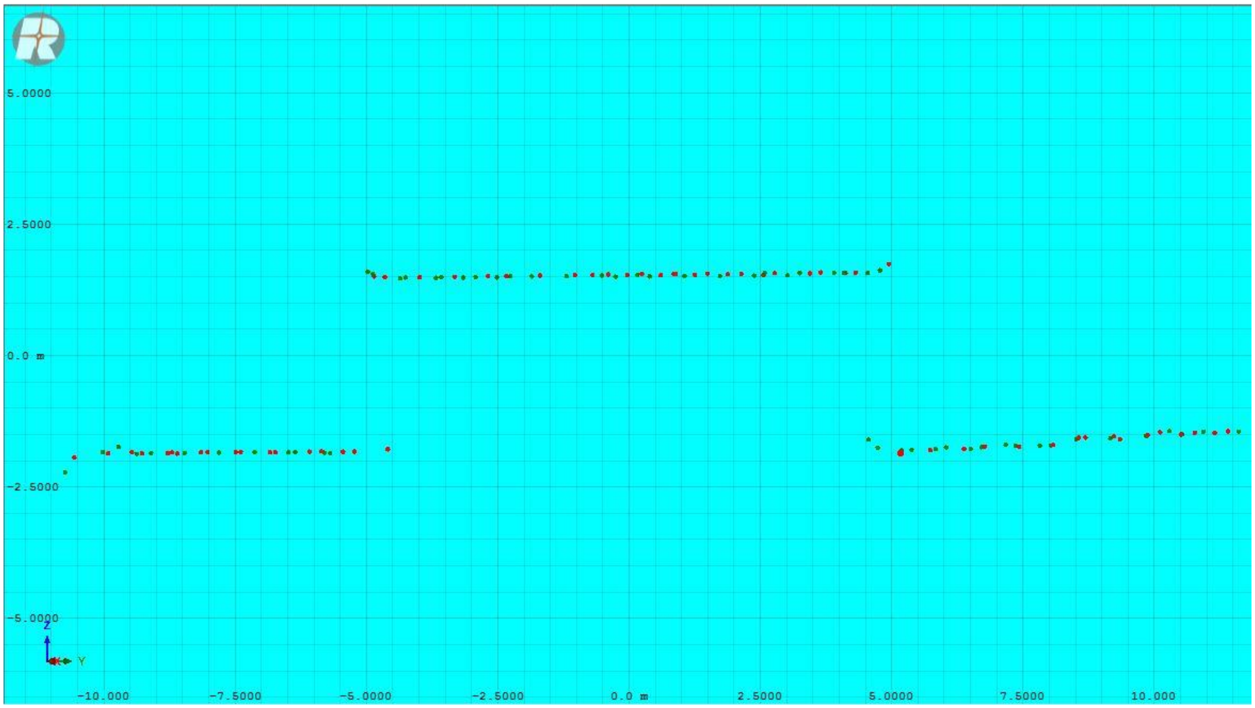


Figure 6 – Profile view cross section of multiple swaths.

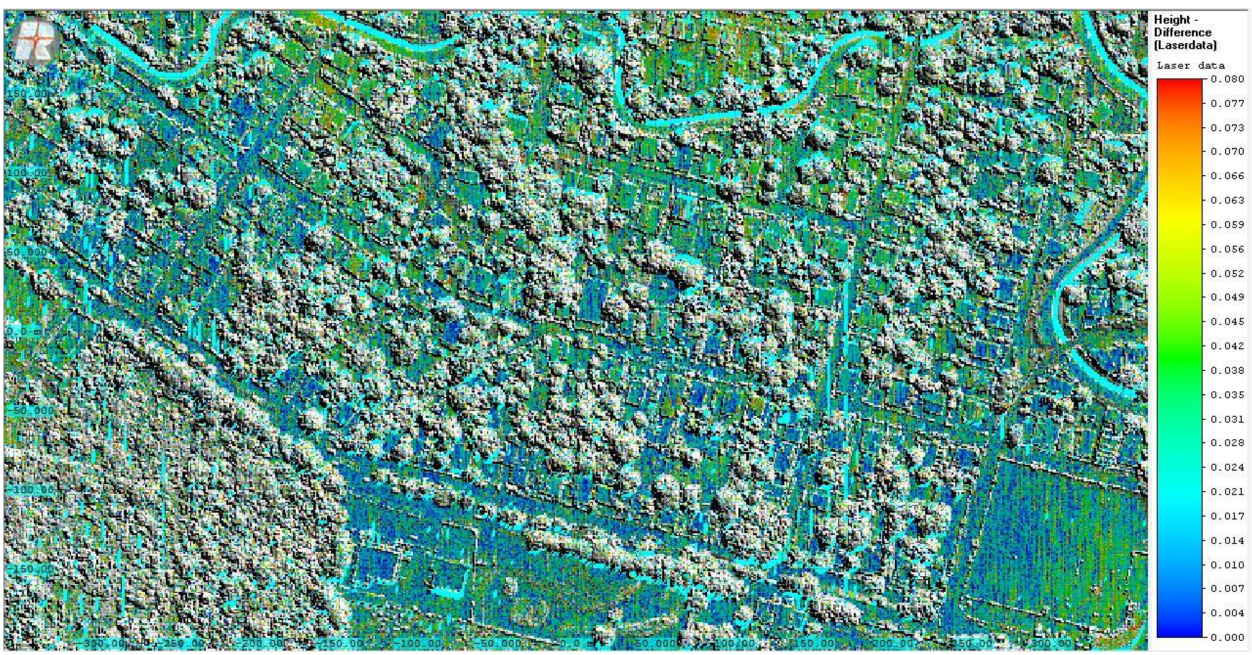


Figure 7 – QC block colored by elevation difference to ensure accuracy at swath edges.

A different set of QC blocks are generated for final review after all transformations have been applied.

PRELIMINARY VERTICAL ACCURACY ASSESSMENT

A preliminary $RMSE_z$ error check is performed by Leading Edge Geomatics at this stage of the project life cycle in the raw lidar dataset against GPS static and kinematic data and compared to $RMSE_z$ project specifications. The lidar data is examined in non-vegetated, flat areas away from breaks. Lidar ground points for each flight line generated by an automatic classification routine are used.

Prior to delivery to Dewberry, the elevation data was verified internally to ensure it met Non-vegetated Vertical Accuracy (NVA) requirements ($RMSE_z \leq 10$ cm and $Accuracy_z$ at the 95% confidence level ≤ 19.6 cm) when compared to static and kinematic GPS checkpoints. Below is a summary for the test:

The calibrated Puerto Rico lidar dataset was tested to 0.163 m vertical accuracy at 95% confidence level based on $RMSE_z$ (0.083 m x 1.9600) when compared to 837 GPS static check points.

The following are the final statistics for the GPS static checkpoints used by Leading Edge Geomatics to internally verify vertical accuracy.

Average dz	0.062 m
Root mean square	0.083 m
Std deviation	0.055 m

Overall the calibrated lidar data products collected by LEG meet or exceed the requirements set out in the Statement of Work. The quality control requirements of LEG quality management program were adhered to throughout the acquisition stage for this project to ensure product quality.

Lidar Processing & Qualitative Assessment

INITIAL PROCESSING

Once Dewberry receives the calibrated swath data from the acquisition provider, Dewberry performs several validations on the dataset prior to starting full-scale production on the project. These validations include vertical accuracy of the swath data, inter-swath (between swath) relative accuracy validation, intra-swath (within a single swath) relative accuracy validation, verification of horizontal alignment between swaths, and confirmation of point density and spatial distribution. This initial assessment allows Dewberry to determine if the data are suitable for full-scale production. Addressing issues at this stage allows the data to be corrected while imposing the least disruption possible on the overall production workflow and overall schedule.

Final Swath Vertical Accuracy Assessment

Once Dewberry received the calibrated swath data from LEG, Dewberry tested the vertical accuracy of the non-vegetated terrain swath data prior to additional processing. Dewberry tested the vertical accuracy of the swath data using the one hundred twenty five (125) non-vegetated (open terrain and urban) independent survey check points. The vertical accuracy is tested by comparing survey checkpoints in non-vegetated terrain to a triangulated irregular network (TIN) that is created from the raw swath points. Only checkpoints in non-vegetated terrain can be tested against raw swath data because the data has not undergone classification techniques to remove vegetation, buildings, and other artifacts from the ground surface. Checkpoints are always compared to interpolated surfaces from the lidar point cloud because it is unlikely that a survey checkpoint will be located at the location of a discrete lidar point. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project. Project specifications require a NVA of 19.6 cm based on the $RMSE_z$ (10 cm) x 1.96. The dataset for the Puerto Rico Lidar Project satisfies this criteria. This raw lidar swath data set was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm $RMSE_z$ Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ = 9.7 cm, equating to +/- 19.0 cm at 95% confidence level. Table 3 shows all calculated statistics for the raw swath data.

100 % of Totals	# of Points	$RMSE_z$ NVA Spec=0.10 m	NVA –Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=0.196 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Min (m)	Max (m)	Kurtosis
Non-Vegetated Terrain	125	0.097	0.190	-0.011	-0.023	1.106	0.097	-0.254	0.467	3.818

Table 3: NVA at 95% Confidence Level for Raw Swaths

Three (3) checkpoints were removed from the raw swath vertical accuracy testing. Two points (NVA-27 and NVA-41) were located underneath power lines, and one point (NVA-85) was located within the data void found in the southeast region of Puerto Rico's mainland. For further information on this data void, see the *Data Voids* section of this report. Only non-vegetated terrain checkpoints are used to test the raw swath data because the raw swath data has not been classified to remove vegetation, structures, and other above ground features from the ground classification. While NVA-27 and NVA-41 are located in open terrain, the overhead power lines are modeled by the lidar point cloud. These high points caused erroneous high values during the swath vertical accuracy testing so these points were removed from the final calculations. Once the data underwent the classification process, the power lines were removed from the final ground classification and these two points could be used in the final vertical accuracy testing for the fully classified lidar data. Table 4, below, provides the coordinates for all three checkpoints. Figure 8, below, shows a profile view of the lidar point cloud and the location of the checkpoint beneath a power line, as well as the corresponding intensity image.

Point ID	NAD83(2011) State Plane PR		PRVD02 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Survey Z (m)
NVA-27	143361.022	234382.655	784.062
NVA-41	167699.617	231317.998	896.531
NVA-85	228041.671	235139.849	53.530

Table 4: Checkpoints removed from raw swath vertical accuracy testing

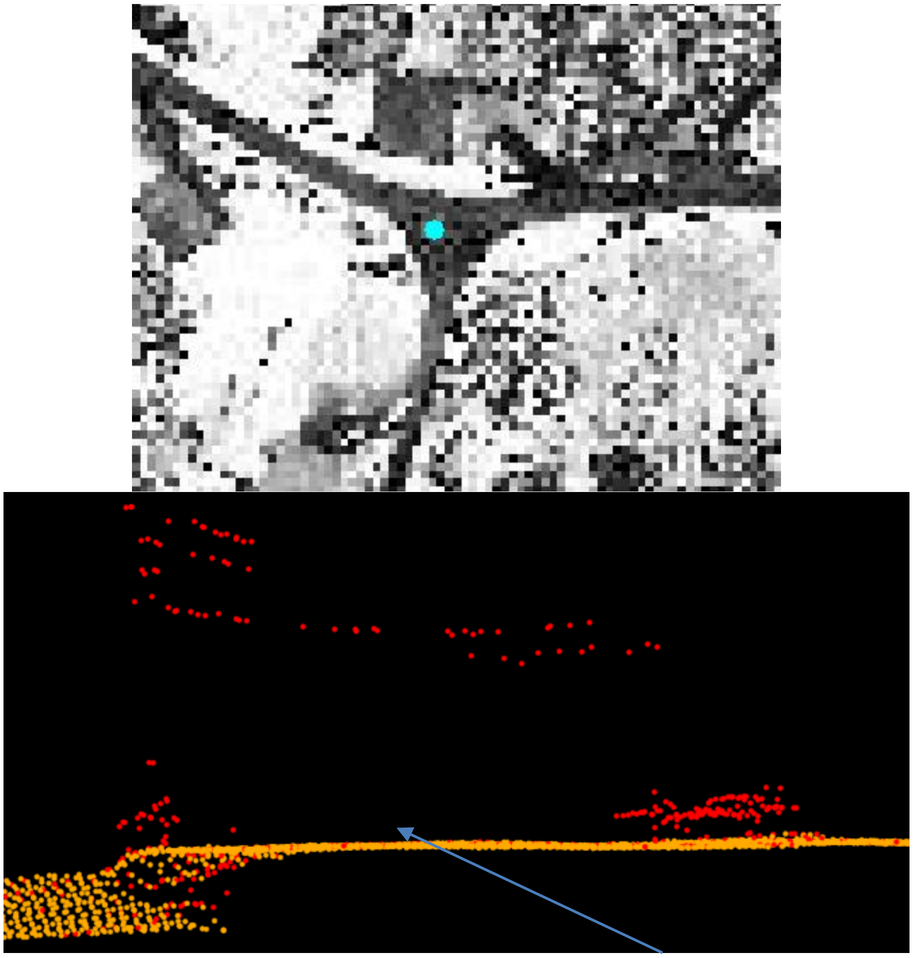


Figure 8 – The intensity image (top) shows the location of non-vegetated point, NVA-41, in blue. This point is located underneath power line features, which is exemplified in the lidar profile (bottom). This point was removed from raw swath vertical accuracy testing because above ground features, including power lines, have not been separated from the ground classification yet.

Inter-Swath (Between Swath) Relative Accuracy

Dewberry verified inter-swath or between swath relative accuracy of the dataset by creating Delta-Z (DZ) orthos. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet inter-swath relative accuracy of 8 cm RMSDz or less with maximum differences less than 16 cm. These measurements are to be taken in non-vegetated and flat open terrain using single or only returns from all classes. Measurements are calculated in the DZ orthos on 1-meter pixels or cell sizes. Areas in the dataset where overlapping flight lines are within 8 cm of each other within each pixel are colored green, areas in the dataset where overlapping flight lines have elevation differences in each pixel between 8 cm to 16 cm are colored yellow, and areas in the dataset where overlapping flight lines have elevation differences in each pixel greater than 16 cm are colored red. Pixels that do not contain points from overlapping flight lines are colored according to their intensity values. Areas of vegetation and steep slopes (slopes with 16 cm or more of valid elevation change across 1 linear meter) are expected to appear yellow or red in the DZ orthos. If the project area is heavily vegetated, Dewberry may also create DZ Orthos from the initial ground classification only, while keeping all other parameters consistent. This allows Dewberry to review the ground classification relative accuracy beneath vegetation and to ensure flight line ridges or other issues do not exist in the final classified data.

Flat, open areas are expected to be green in the DZ orthos. Large or continuous sections of yellow or red pixels can indicate the data was not calibrated correctly or that there were issues during acquisition that could affect the usability of the data, especially when these yellow/red sections follow the flight lines and not the terrain or areas of vegetation. The DZ orthos for the Puerto Rico QL2 Lidar Project are shown in the figure below; this project meets inter-swath relative accuracy specifications.

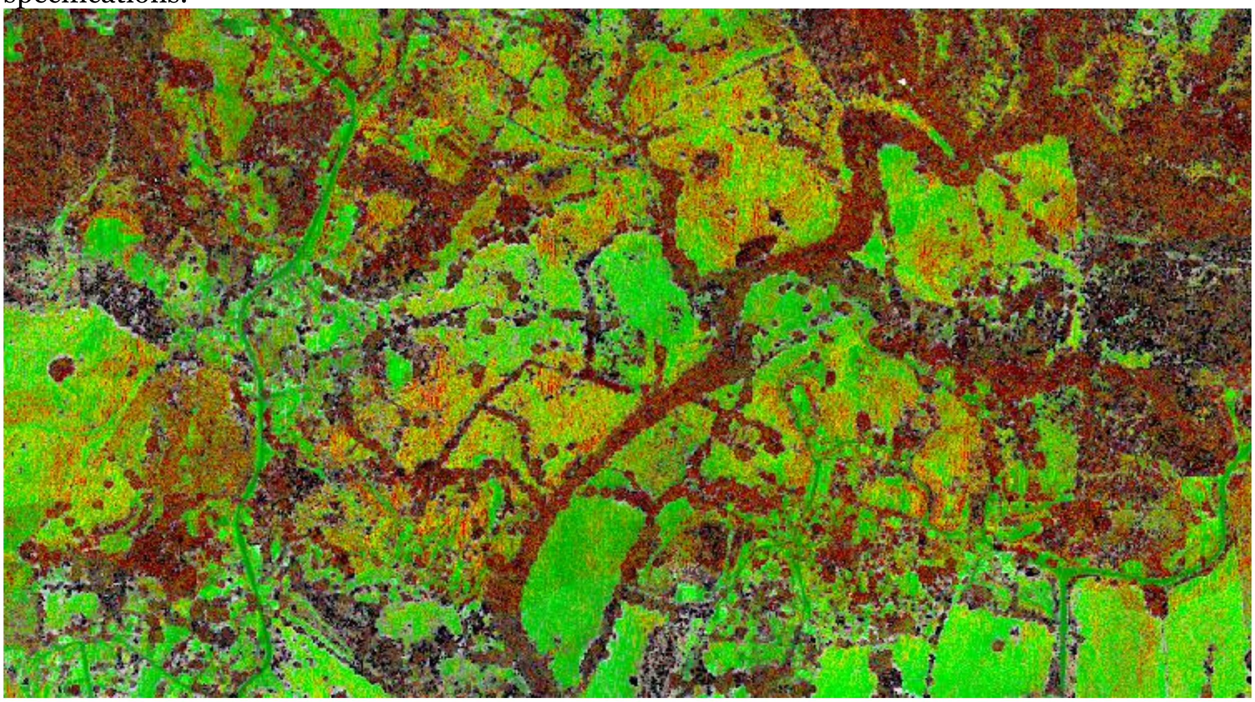


Figure 9– Single return DZ Orthos for the Puerto Rico QL2 Lidar Project. Inter-swath relative accuracy passes specifications.

Intra-Swath (Within a Single Swath) Relative Accuracy

Dewberry verifies the intra-swath or within swath relative accuracy by using Quick Terrain Modeler (QTM) scripting and visual reviews. QTM scripting is used to calculate the maximum difference of all points within each 1-meter pixel/cell size of each swath. Dewberry analysts then identify planar surfaces acceptable for repeatability testing and analysts review the QTM results in those areas. According to the SOW, USGS Lidar Base Specifications v1.2, and ASPRS Positional Accuracy Standards for Digital Geospatial Data, 10 cm Vertical Accuracy Class or QL2 data must meet intra-swath relative accuracy of 6 cm maximum difference or less. The image below shows two examples of the intra-swath relative accuracy of the Puerto Rico lidar data; this project meets intra-swath relative accuracy specifications.

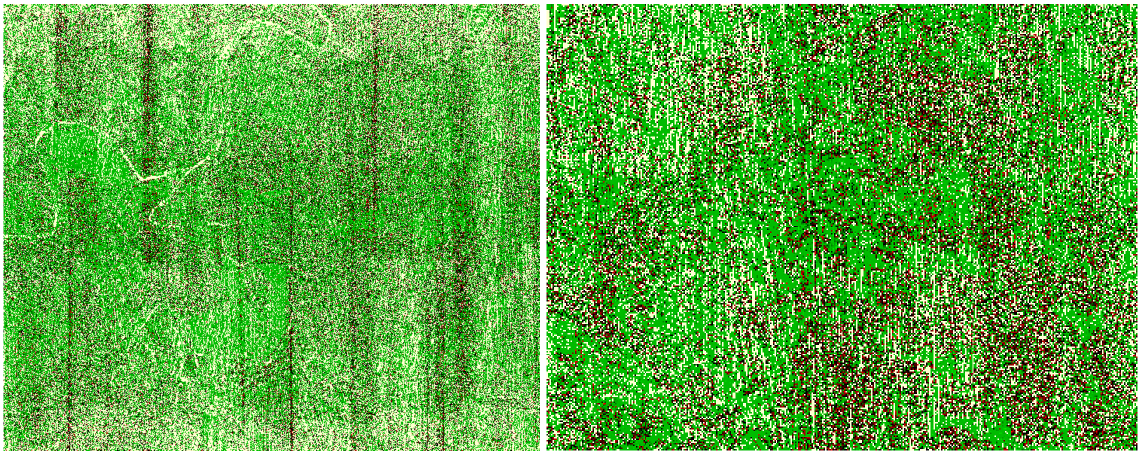


Figure 10–Intra-swath relative accuracy. The left image shows a large portion of the dataset; flat, open areas are colored green as they are within 6 cm whereas sloped terrain is colored red because it exceeds 6 cm maximum difference, as expected, due to actual slope/terrain change. The right image is a close-up of a flat area. With the exception of few trees (shown in red as the elevation/height difference in vegetated areas will exceed 6 cm) this open flat area is acceptable for repeatability testing. Intra-swath relative accuracy passes specifications.

Horizontal Alignment

To ensure horizontal alignment between adjacent or overlapping flight lines, Dewberry uses QTM scripting and visual reviews. QTM scripting is used to create files similar to DZ orthos for each swath but this process highlights planar surfaces, such as roof tops. In particular, horizontal shifts or misalignments between swaths on roof tops and other elevated planar surfaces are highlighted. Visual reviews of these features, including additional profile verifications, are used to confirm the results of this process. The image below shows an example of the horizontal alignment between swaths for the Puerto Rico lidar data.

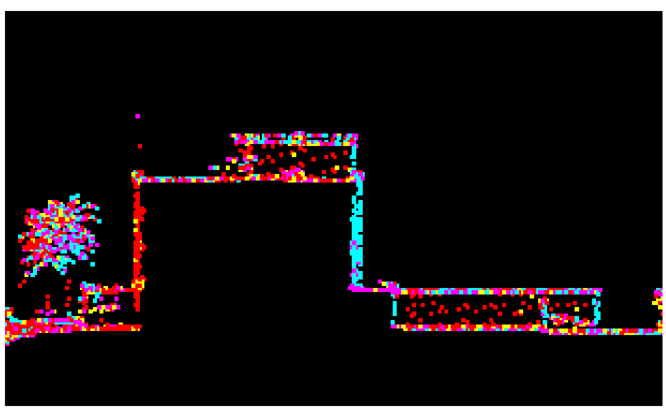


Figure 11– Horizontal Alignment. Multiple flight lines differentiated by color are shown in this profile. There is no visible offset between these flight lines. No horizontal alignment issues were identified.

Point Density and Spatial Distribution

The required Aggregate Nominal Point Spacing (ANPS) for this project is no greater than 0.7 meters, which equates to an Aggregate Nominal Point Density (ANPD) of 2 points per square meter or greater. Density calculations were performed using first return data only located in the geometrically usable center portion (typically ~90%) of each swath. By utilizing statistics, the project area was determined to have an ANPS of 0.39 meters or an ANPD of 6.55 points per square meter which satisfies the project requirements.

The spatial distribution of points must be uniform and free of clustering. This specification is tested by creating a grid with cell sizes equal to the design NPS*2. QTM scripting is then used to calculate the number of first return points of each swath within each grid cell. At least 90% of the cells must contain 1 lidar point, excluding acceptable void areas such as water or low NIR reflectivity features, i.e. some asphalt and roof composition materials. This project passes spatial distribution requirements, as shown in Figure 12.

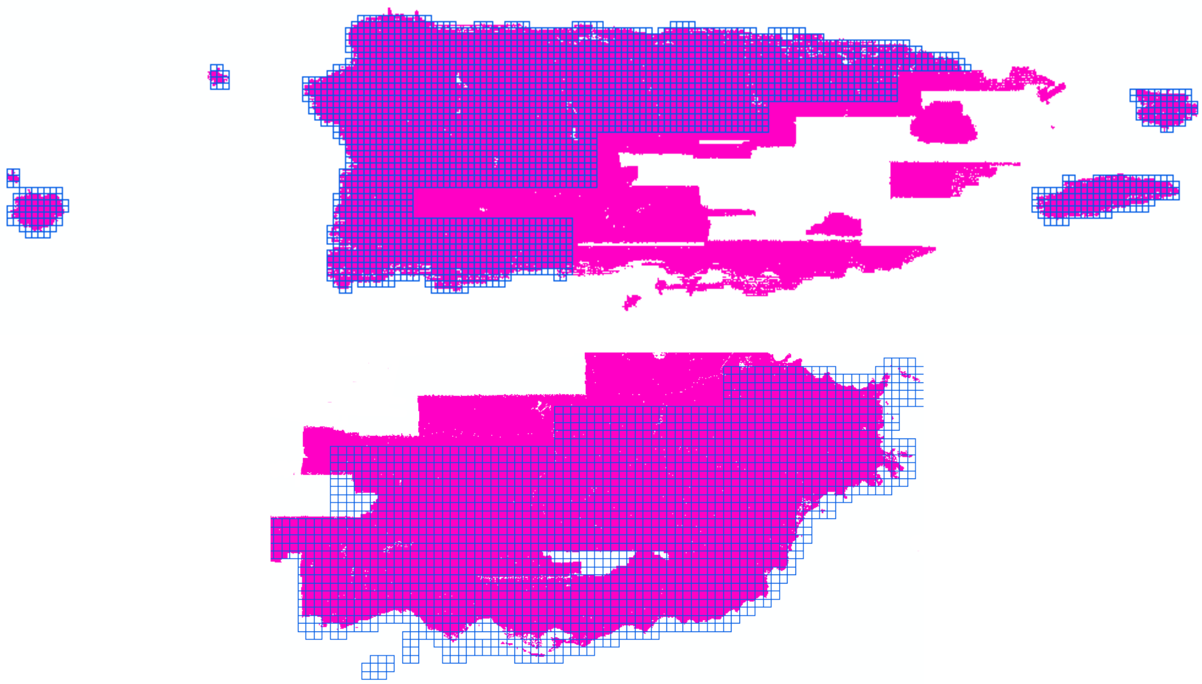


Figure 12– Spatial Distribution. The 2*NPS tile grid is shown in blue and all tiles containing at least one lidar point are colored pink. Top – Delivery 1, Bottom – Delivery 2.

DATA CLASSIFICATION AND EDITING

Once the calibration, absolute swath vertical accuracy, and relative accuracy of the data was confirmed, Dewberry utilized a variety of software suites for data processing. The data was processed using GeoCue and TerraScan software. The initial step is the setup of the GeoCue project, which is done by importing a project defined tile boundary index encompassing the entire project area. The acquired 3D laser point clouds, in LAS binary format, were imported into the GeoCue project and tiled according to the project tile grid. Once tiled, the laser points were classified using a proprietary routine in TerraScan. This routine classifies any obvious low outliers in the dataset to class 7 and high outliers in the dataset to class 18. Points along flight line edges that are geometrically unusable are identified as withheld and classified to a separate class so that they will not be used in the initial ground algorithm. After points that could negatively affect the ground are removed from class 1, the ground layer is extracted from this remaining point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

This surface model is generated using three main parameters: building size, iteration angle and iteration distance. The initial model is based on low points being selected by a "roaming window" with the assumption that these are the ground points. The size of this roaming window is determined by the building size parameter. The low points are triangulated and the remaining points are evaluated and subsequently added to the model if they meet the iteration angle and distance constraints. This process is repeated until no additional points are added within iterations. A second critical parameter is the maximum terrain angle constraint, which determines the maximum terrain angle allowed within the classification model.

Each tile was then imported into Terrascan and a surface model was created to examine the ground classification. Dewberry analysts visually reviewed the ground surface model and corrected errors in the ground classification such as vegetation, buildings, and bridges that were present following the initial processing conducted by Dewberry. Dewberry analysts employ 3D visualization techniques to view the point cloud at multiple angles and in profile to ensure that non-ground points are removed from the ground classification. Bridge decks are classified to class 17 using bridge breaklines compiled by Dewberry. After the ground classification corrections were completed, the dataset was processed through a water classification routine that utilizes breaklines compiled by Dewberry to automatically classify hydro features. The water classification routine selects ground points within the breakline polygons and automatically classifies them as class 9, water. During this water classification routine, points that are within 1x NPS or less of the hydrographic features are moved to class 10, an ignored ground due to breakline proximity. Overage points are then identified in Terrascan and GeoCue is used to set the overlap bit for the overage points and the withheld bit is set on the withheld points previously identified in Terrascan before the ground classification routine was performed. There are no ground points flagged as overlap as all ground points were used in DEM generation to maintain the highest density possible (there are class 1 overlap points). The ground was reviewed to ensure no unwanted elevation variability results from using all ground points. Unusable points along the edges of flight lines have been flagged as withheld.

The lidar tiles were classified to the following classification schema:

- Class 1 = Unclassified, used for all other features that do not fit into the Classes 2, 7, 9, 10, 17, or 18, including vegetation, buildings, etc.
- Class 2 = Bare-Earth Ground
- Class 7 = Low Noise
- Class 9 = Water, points located within collected breaklines
- Class 10 = Ignored Ground due to breakline proximity
- Class 17 = Bridge Decks
- Class 18 = High Noise

After manual classification, the LAS tiles were peer reviewed and then underwent a final QA/QC. After the final QA/QC and corrections, all headers, appropriate point data records, and variable length records, including spatial reference information, are updated in GeoCue software and then verified using proprietary Dewberry tools.

Lidar Qualitative Assessment

Dewberry's qualitative assessment utilizes a combination of statistical analysis and interpretative methodology or visualization to assess the quality of the data for a bare-earth digital terrain model (DTM). This includes creating pseudo image products such as lidar orthos produced from the intensity returns, Triangular Irregular Network (TIN)'s, Digital Elevation Models (DEM) and 3-dimensional models as well as reviewing the actual point cloud data. This process looks for anomalies in the data, areas where man-made structures or vegetation points may not have been classified properly to produce a bare-earth model, and other classification errors. This report will present representative examples where the lidar and post processing had issues as well as examples of where the lidar performed well.

VISUAL REVIEW

The following sections describe common types of issues identified in lidar data and the results of the visual review for the Puerto Rico lidar data.

Data Voids

The LAS files are used to produce density grids using the commercial software package QT Modeler (QTM) which creates a 3-dimensional data model derived from Class 2 (ground) points in the LAS files. Grid spacing is based on the project density deliverable requirement for un-obscured areas. Acceptable voids (areas with no lidar returns in the LAS files) that are present in the majority of lidar projects include voids caused by bodies of water. Dewberry did not identify any unacceptable voids where lidar data was acquired in Puerto Rico.

However, Data voids illustrated in the below figure are present in the southeast region of Puerto Rico's mainland. Lidar data could not be collected in this area due to persistent cloud cover that prevented the lidar pulse from penetrating the terrain.

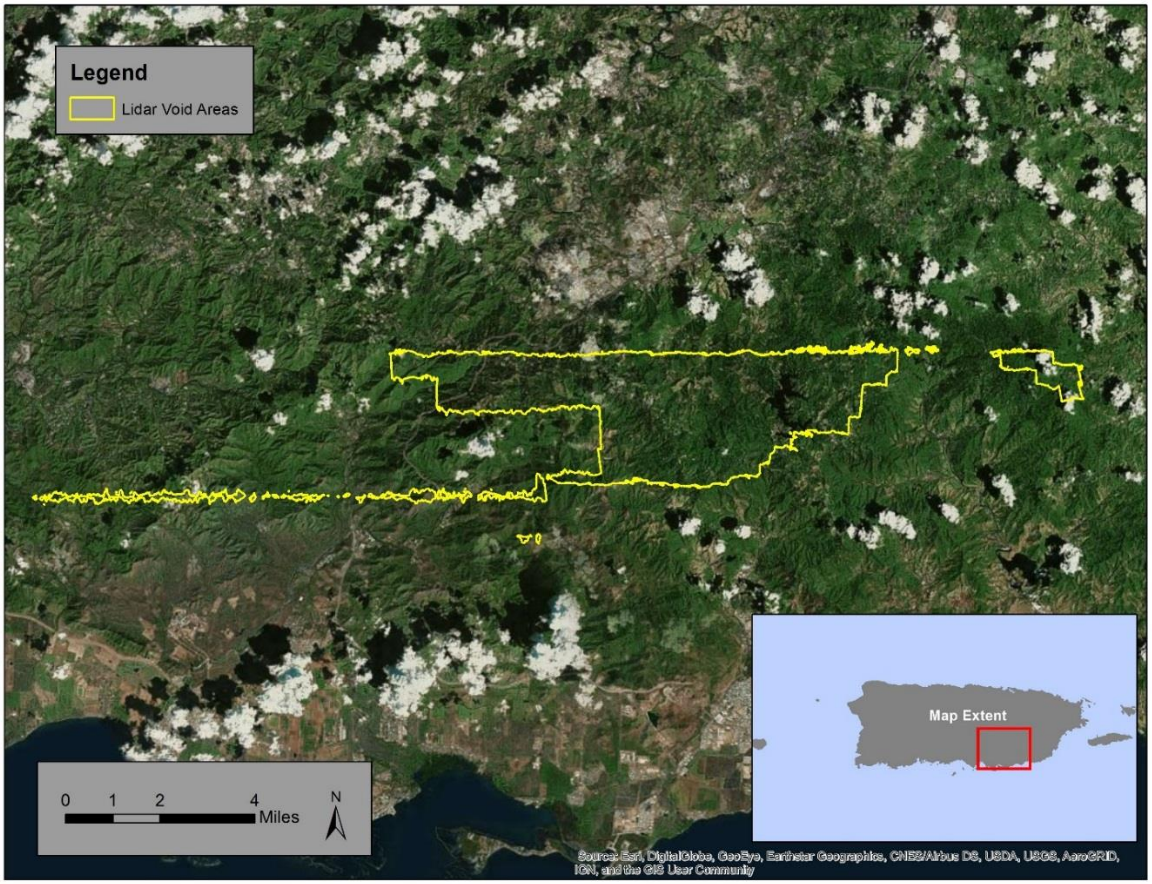


Figure 13– Lidar data was unable to be collected in the area outlined in yellow due to persistent cloud cover that prevented the lidar pulse from penetrating the bare ground.

Artifacts

Artifacts are caused by the misclassification of ground points and usually represent vegetation and/or man-made structures. The artifacts identified are usually low lying structures, such as porches or low vegetation used as landscaping in neighborhoods and other developed areas. These low lying features are extremely difficult for the automated algorithms to detect as non-ground and must be removed manually. The vast majority of these features have been removed but a small number of these features are still in the ground classification. The limited numbers of features remaining in the ground are usually 0.3 meters or less above the actual ground surface, and should not negatively impact the usability of the dataset.

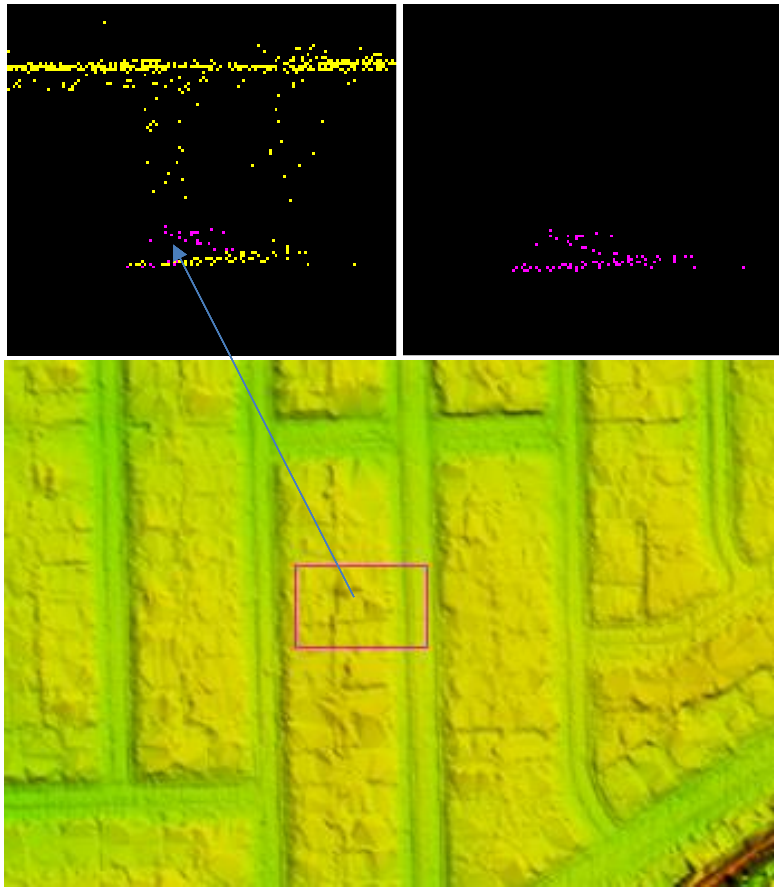


Figure 14 – Tile number 20QJF49506300. Profile with points colored by class (class 1=yellow, class 2=pink) is shown in the top left view and the right view shows only class 2. A TIN of the surface is shown in the bottom view. The arrow identifies low vegetation points. A limited number of these small features are still classified as ground as shown in the upper right view but do not impact the usability of the dataset.

Bridge Removal Artifacts

The DEM surface models are created from TINs or Terrains. TIN and Terrain models create continuous surfaces from the inputs. Because a continuous surface is being created, the TIN or Terrain will use interpolation to continue the surface beneath the bridge where no lidar data was acquired. Locations where bridges were removed will generally contain less detail in the bare-earth surface because these areas are interpolated.

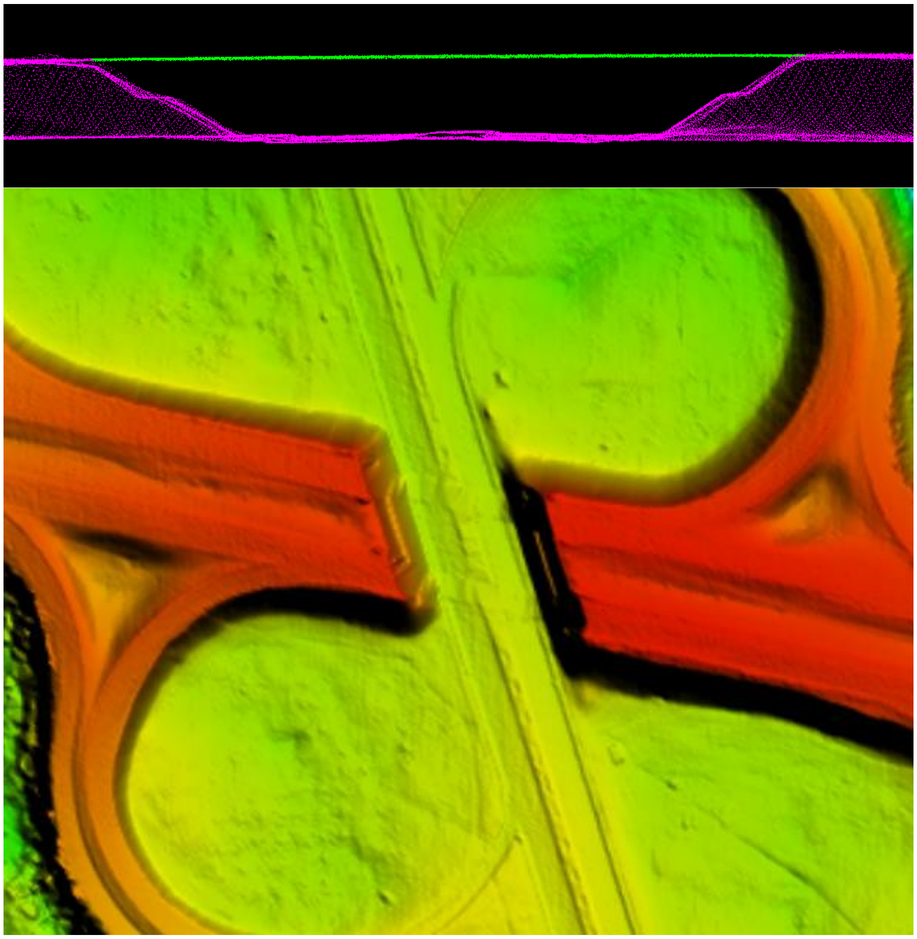


Figure 15 – Tile number 19QGA68506750. The DEM in the bottom view shows an area where a bridge has been removed from ground. The surface model must make a continuous model and in order to do so, points are connected through interpolation. This results in less detail where the surface must be interpolated. The profile in the top view shows the lidar points of this particular feature colored by class. All bridge points have been removed from ground (pink) and are reclassified to bridge decks (green).

Culverts and Bridges

Bridges have been removed from the bare earth surface while culverts remain in the bare earth surface. In instances where it is difficult to determine if the feature is a culvert or bridge, such as with some small bridges, Dewberry erred on assuming they would be culverts especially if they are on secondary or tertiary roads. Below is an example of a culvert that has been left in the ground surface.

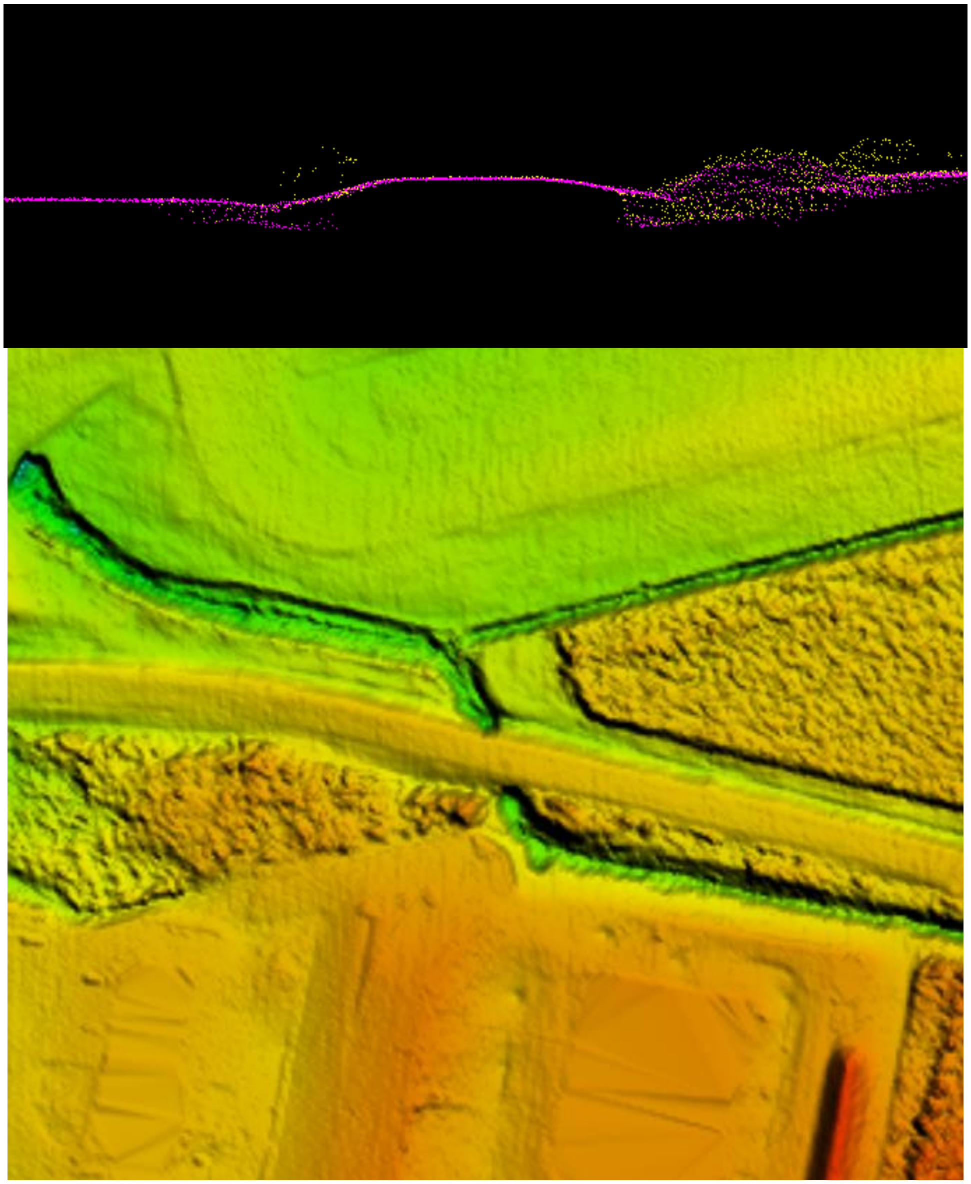


Figure 16– Tile number 19QFA23504650. Profile with points colored by class (class 1=yellow, class 2=pink) is shown in the top view and the DEM is shown in the bottom view. This culvert remains in the bare earth surface. Bridges have been removed from the bare earth surface and classified to class 1.

In Ground Structures

In ground structures exist within the project area. These types of structures occur mainly on military bases and in facilities designed for munitions testing and storage. These features are correctly included in the ground classification.

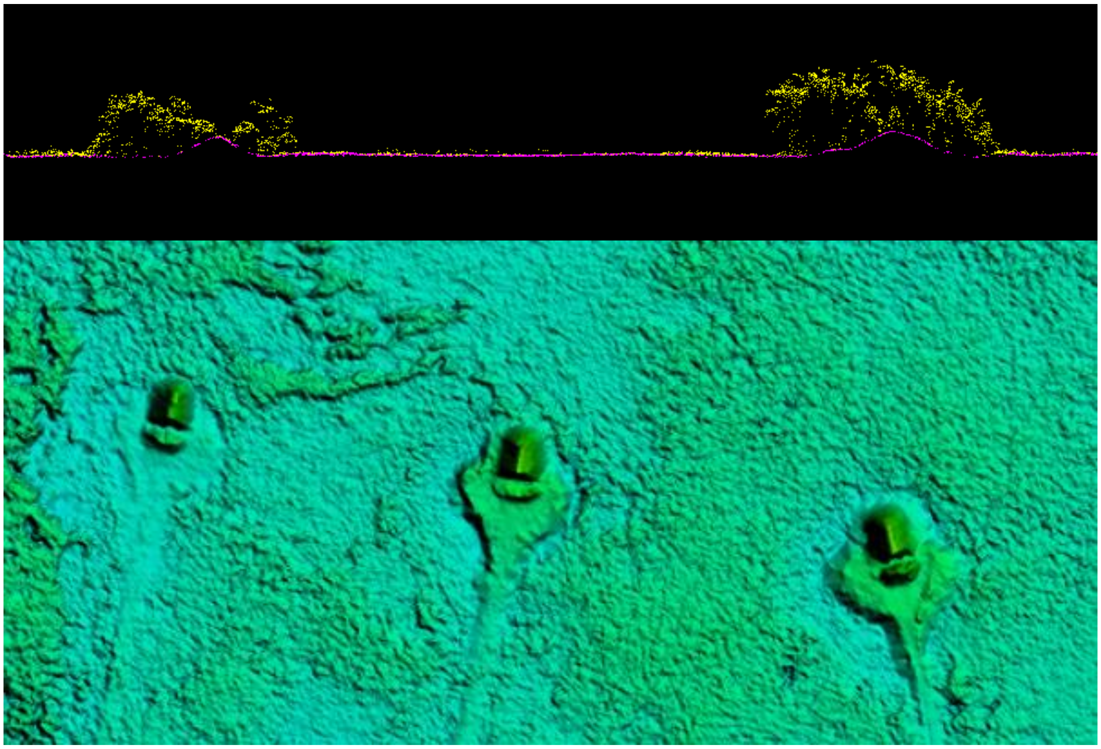
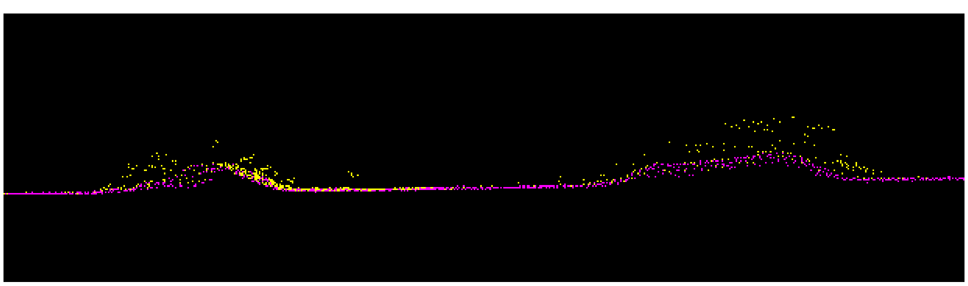


Figure 17 – Tile number 19QGA22506600. Profile with the points colored by class (class 1=yellow, class 2=pink) is shown in the top view and a DEM of the surface is shown in the bottom view. These features are correctly included in the ground classification.

Dirt Mounds

Irregularities in the natural ground exist and may be misinterpreted as artifacts that should be removed. Small hills and dirt mounds are present throughout the project area. These features are correctly included in the ground.



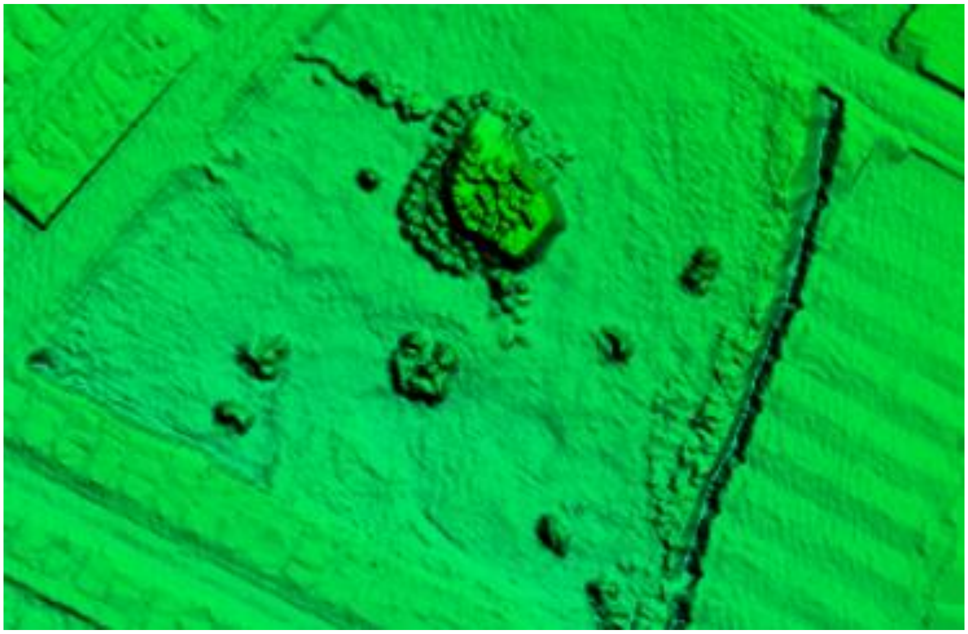


Figure 18 - Tile number 19QFA25005100. Profile with the points colored by class (class 1=yellow, class 2=pink) is shown in the top view and a DEM of the surface is shown in the bottom view. These features are correctly included in the ground classification.

Elevation Change Within Breaklines

While water bodies are flattened in the final DEMs, other features such as linear hydrographic features can have significant changes in elevation within a small distance. In linear hydrographic features, this is often due to the presence of a structure that affects flow such as a dam or spillway. Dewberry has reviewed the DEMs to ensure that changes in elevation are shown from bank to bank. These changes are often shown as steps to reduce the presence of artifacts while ensuring consistent downhill flow. An example is shown below.

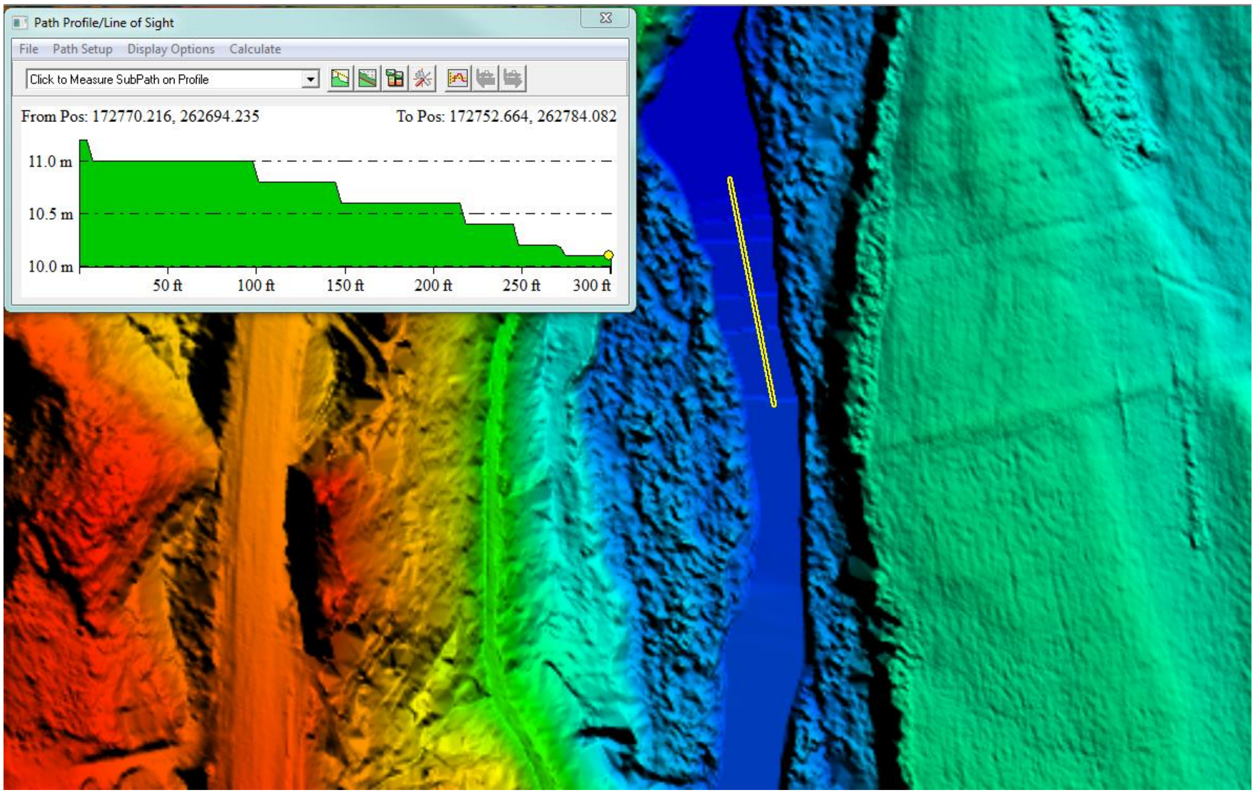


Figure 19 – Tile 19QGA73006000. Elevation change has been stair stepped. The steps are flat from bank to bank and flow consistently downhill.

Agricultural Areas

Puerto Rico's landscape consists of extensive agricultural areas. During Dewberry's review of the topographic lidar point cloud data we identified areas with low (~0.5 ft – 1 ft) to medium height vegetation (~1 ft – 2 ft). These areas are often located where there is a combination of pasture grass and emergent wetland vegetation. Based on our broad field experience in Puerto Rico these pasturelands are typically irrigated and have hydraulic structures in place to maintain water levels. This causes the soil to be saturated making the ground surface spongy in texture. As a result, we found dense vegetation points in the point cloud data without a clear signature of ground points. We have provided an example below to help understand this issue. Figure 20 below shows Low Vegetation (~0.5 ft - 1 ft above "true ground") in an agricultural area. Figure 21 shows the vegetation in a surface model.

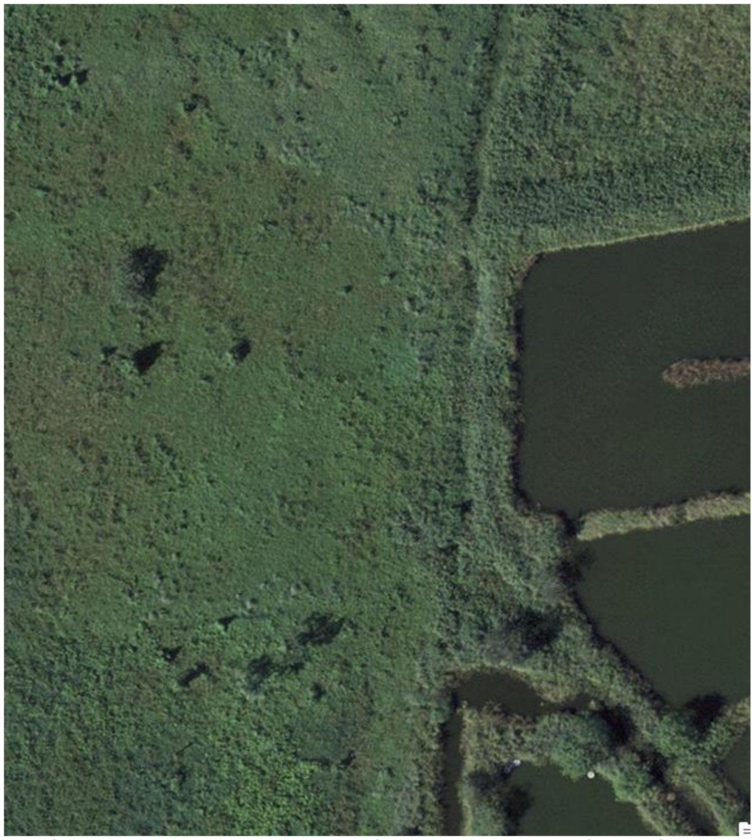


Figure 20 - Tile 19QFA22006000 orthoimage of pasture in agricultural regions

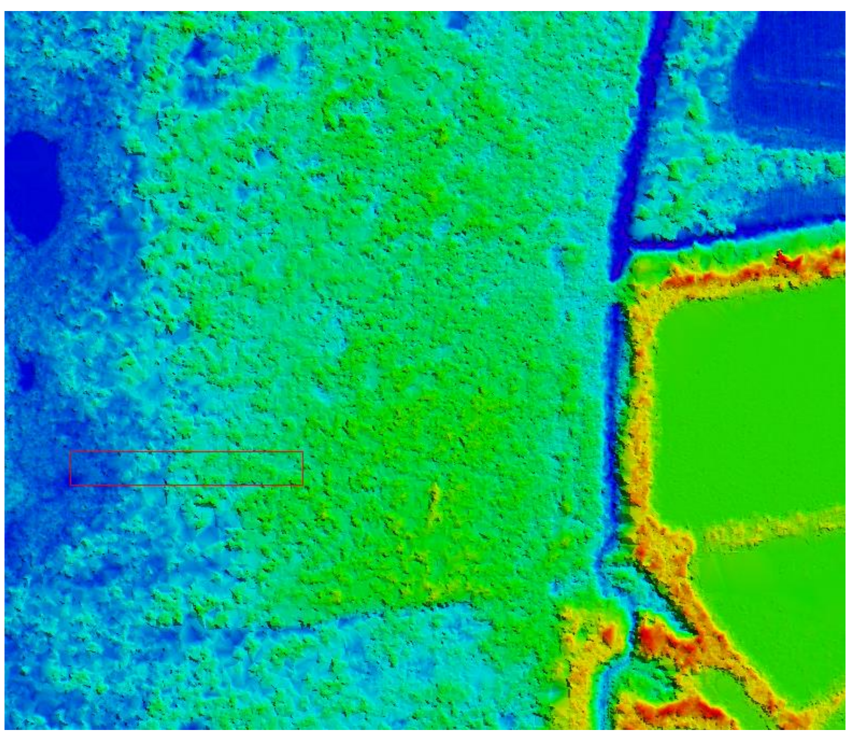


Figure 21 – Tile 19QFA22006000 example of pasture in agricultural regions

In order to produce an accurate and reliable bare-earth DEM with minimal low confidence areas, we maintained points with elevations within 30 cm of the automated ground in the Ground class (Class 2) and manually removed the remaining high points as shown in Figure 22.

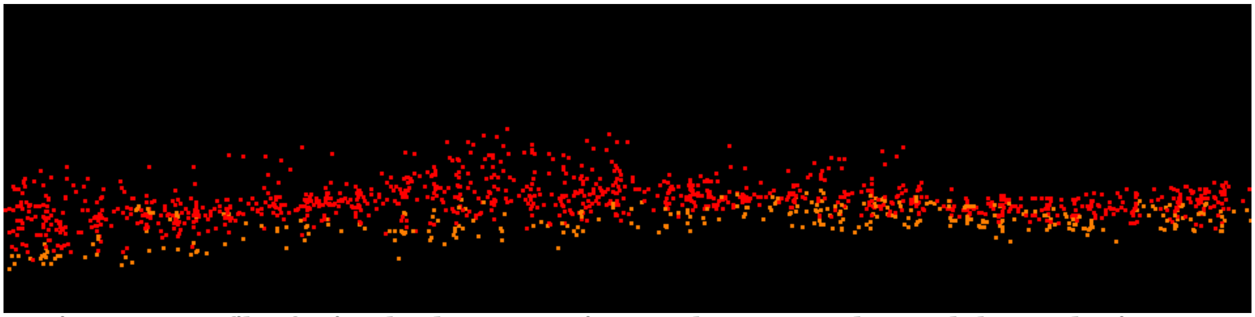


Figure 22 - Profile of point cloud. Orange points are the automated ground class, red points are unclassified.

Marsh Areas

It is sometimes difficult to determine true ground in low wet areas; the lowest points available are used to represent ground. Marsh areas are present within the project area and were not collected with breaklines as they are not open bodies of water. As these areas are not included in the collected breaklines, marsh areas were not flattened in the final DEMs. While low points are used to determine ground in marsh areas, there is often greater variation within the low points due to wet soils that cause greater interpolation between points, and undulating or uneven ground. An example is shown below.

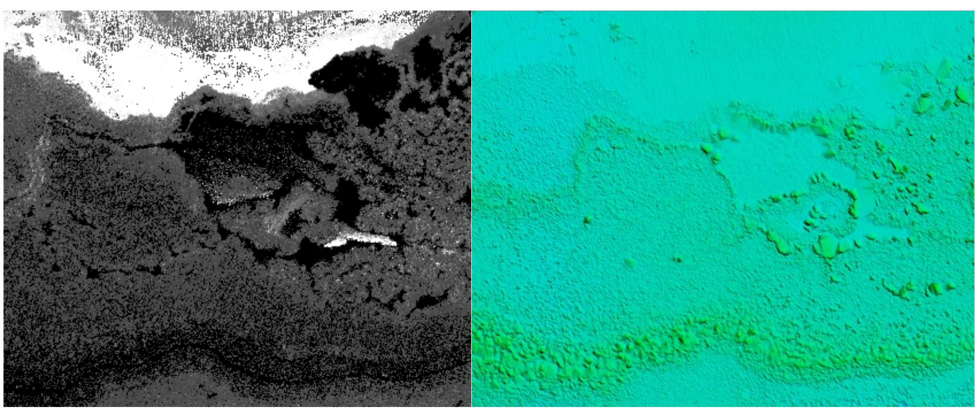


Figure 23 – Tile number 19QFV28001200. The intensity on the left shows a marsh area that was not included in the collected breaklines. The same area is shown in the DEM on the right. Due to wet soils and broken terrain, the point density in marsh areas is sparser than surrounding areas and there is more variation in the low points representing ground.

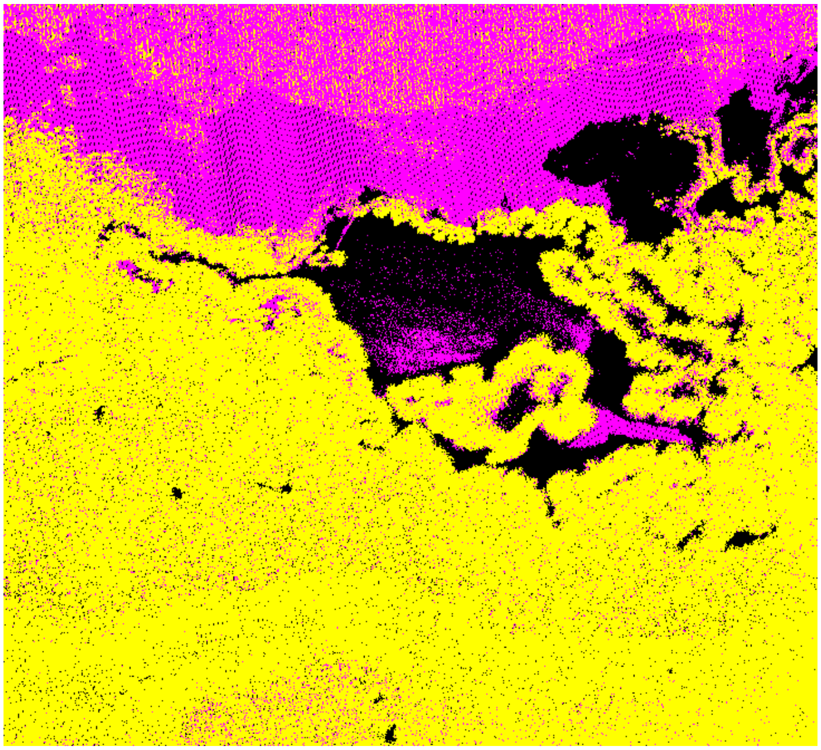


Figure 24 - Tile number 19QFV28001200. The same marsh area shown in the figure above is shown in this image with the points colored by class (class 1=yellow, class 2=pink). Though ground points are sparse they are present, indicating that the area is wet but should not be classified as water (class 9). Doing so would strip the detail from this area and result in incorrectly flattening ground as part of the hydro mask.

Flight line Ridges

Ridges occur when there is a difference between the elevations of adjoining flight lines or swaths. Some flight line ridges are visible in the final DEMs but they do not exceed the project specifications and the overall relative accuracy requirements for the project area have been met. An example of a visible ridge that is within tolerance is shown below.

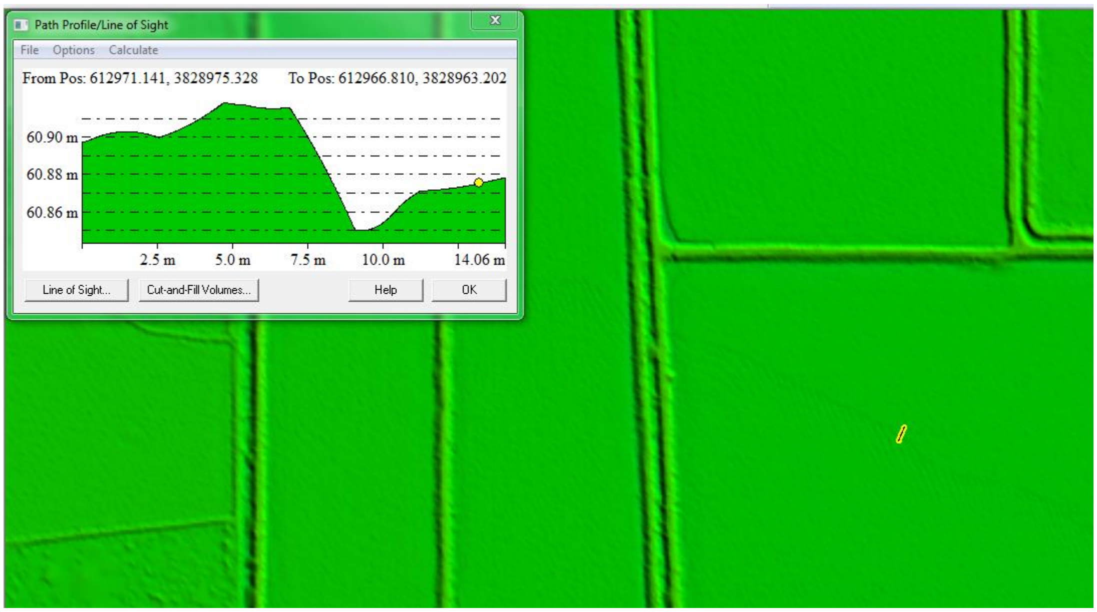


Figure 25– Tile number 15SXU120280. The flight line ridge is less than 8 cm. Overall, the Puerto Rico QL2 lidar data meets the project specifications for 8 cm RMSDz relative accuracy.

FORMATTING

After the final QA/QC is performed and all corrections have been applied to the dataset, all lidar files are updated to the final format requirements and the final formatting, header information, point data records, and variable length records are verified using Dewberry proprietary tools. The table below lists some of the main lidar header fields that are updated and verified.

Classified Lidar Formatting		
Parameter	**Requirement**	**Pass/Fail**
LAS Version	1.4	Pass
Point Data Format	Format 6	Pass
Coordinate Reference System	NAD83 (2011) State Plane Puerto Rico Zone 5200, meters and PRVD02 (Geoid 12B), meters in WKT Format	Pass
Global Encoder Bit	Should be set to 17 for Adjusted GPS Time	Pass
Time Stamp	Adjusted GPS Time (unique timestamps)	Pass

System ID	Should be set to the processing system/software and is set to NIIRS10 for GeoCue software	Pass
Multiple Returns	The sensor shall be able to collect multiple returns per pulse and the return numbers are recorded	Pass
Intensity	16 bit intensity values are recorded for each pulse	Pass
Classification	Required Classes include: Class 1: Unclassified Class 2: Ground Class 7: Low Noise Class 9: Water Class 10: Ignored Ground Class 17: Bridge Decks Class 18: High Noise	Pass
Overlap and Withheld Points	Overlap (Overage) and Withheld points are set to the Overlap and Withheld bits. There are no ground points flagged as overlap as all ground points were used in DEM generation to maintain the highest density possible (there are class 1 overlap points). The ground was reviewed to ensure no unwanted elevation variability results from using all ground points. Unusable points along the edges of flight lines have been flagged as withheld.	Pass
Scan Angle	Recorded for each pulse	Pass
XYZ Coordinates	Unique Easting, Northing, and Elevation coordinates are recorded for each pulse	Pass

Derivative Lidar Products

USGS required several derivative lidar products to be created. Each type of derived product is described below.

LOW CONFIDENCE POLYGONS

Low confidence polygons have been delivered with this dataset. These polygons represent areas where heavy vegetation greatly diminishes penetration of the lidar pulse, resulting in a bare earth surface that is potentially less accurate due to the lack of lidar returns from the ground beneath the vegetation. Low confidence polygons delineate areas where conformance to VVA standards may not be met. The low confidence polygons created for this dataset were delineated according to the criteria and assumptions outlined in the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014). Low confidence areas are identified using a ground density raster. All areas with a Nominal Ground Point Density less than a specified threshold are identified as low confidence cells in the ground density raster. The low confidence cells are exported to polygons and aggregated into larger shapes. Areas of expected low density in the ground, such as water or where buildings/structures have been removed, are deleted from the aggregated low confidence polygons. The size of all polygons are then calculated and polygons below the minimum size threshold are removed from the final low confidence polygon dataset.

Lidar Positional Accuracy

BACKGROUND

Dewberry quantitatively tested the dataset by testing the vertical accuracy of the lidar. The vertical accuracy is tested by comparing the discreet measurement of the survey checkpoints to that of the interpolated value within the three closest lidar points that constitute the vertices of a three-dimensional triangular face of the TIN. Therefore, the end result is that only a small sample of the lidar data is actually tested. However there is an increased level of confidence with lidar data due to the relative accuracy. This relative accuracy in turn is based on how well one lidar point "fits" in comparison to the next contiguous lidar measurement, and is verified as part of the initial processing. If the relative accuracy of a dataset is within specifications and the dataset passes vertical accuracy requirements at the location of survey checkpoints, the vertical accuracy results can be applied to the whole dataset with high confidence due to the passing relative accuracy. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Dewberry also tests the horizontal accuracy of lidar datasets when checkpoints are photo-identifiable in the intensity imagery. Photo-identifiable checkpoints in intensity imagery typically include checkpoints located at the ends of paint stripes on concrete or asphalt surfaces or checkpoints located at 90 degree corners of different reflectivity, e.g. a sidewalk corner adjoining a grass surface. The XY coordinates of checkpoints, as defined in the intensity imagery, are compared to surveyed XY coordinates for each photo-identifiable checkpoint. These differences are used to compute the tested horizontal accuracy of the lidar. As not all projects contain photo-identifiable checkpoints, the horizontal accuracy of the lidar cannot always be tested.

SURVEY VERTICAL ACCURACY CHECKPOINTS

For the final vertical accuracy assessment, two hundred twelve (212) check points were surveyed for the project and are located within bare earth/open terrain, grass/weeds/crops, and forested/fully grown land cover categories. Please see appendix A to view the survey report which details and validates how the survey was completed for this project.

Checkpoints were evenly distributed throughout the project area so as to cover as many flight lines as possible using the "dispersed method" of placement.

Table 5 shown below lists the location of the QA/QC checkpoints used to test the positional accuracy of the dataset.

Point ID	NAD83 (2011) Puerto Rico State Plane		PRVD02 (Geoid 12B)
	Easting X (m)	Northing Y (m)	Elevation (m)
NVA-1	118838.113	216505.018	11.000

NVA-2	121778.117	222115.070	11.435
NVA-3	128061.518	216495.756	59.312
NVA-4	135137.078	215553.612	1.335
NVA-5	133458.703	227941.719	33.135
NVA-6	123292.495	232289.285	41.791
NVA-7	122930.840	244788.763	23.215
NVA-8	123053.129	246945.816	2.670
NVA-9	121553.087	250955.721	1.472
NVA-10	114351.294	254847.859	6.837
NVA-11	124292.732	259565.109	20.534
NVA-12	124745.174	267028.103	123.259
NVA-13	125599.601	273691.828	66.854
NVA-14	136285.844	273245.212	71.556
NVA-15	131956.440	267218.986	169.226
NVA-16	132542.075	253199.709	227.335
NVA-17	137786.750	247245.819	355.967
NVA-18	132399.784	233614.558	44.168
NVA-19	141728.339	229835.307	212.070
NVA-20	141438.307	221751.930	11.194
NVA-21	143775.370	215123.510	37.481
NVA-22	154295.013	222191.741	58.334
NVA-23	159606.973	217407.188	6.017
NVA-24	151836.230	222492.997	49.187
NVA-25	129004.374	240438.600	105.120
NVA-26	142144.100	238789.276	426.399
NVA-27	143361.022	234382.655	784.062
NVA-28	140784.666	246475.806	306.691
NVA-29	136426.530	259041.718	71.757
NVA-30	143570.949	266558.025	186.025
NVA-31	151017.857	269562.096	103.235
NVA-32	148115.255	262419.410	202.462
NVA-33	147955.133	253189.554	375.035
NVA-34	155463.237	247610.718	523.144
NVA-35	156342.312	240100.539	603.664
NVA-36	154788.430	224927.924	74.931
NVA-37	161739.454	222823.971	54.014
NVA-38	164708.268	220080.256	8.650
NVA-39	171112.687	216583.098	4.654
NVA-40	169796.164	224041.401	40.086
NVA-41	167699.617	231317.998	896.531
NVA-42	160940.407	237715.334	574.502
NVA-43	161465.083	242800.429	668.391

NVA-44	160985.526	250566.269	399.344
NVA-45	160419.774	257628.565	313.937
NVA-46	163844.957	263462.571	187.702
NVA-47	163163.607	272393.673	11.858
NVA-48	171289.263	270571.055	1.470
NVA-49	180550.879	261239.930	194.053
NVA-50	174137.747	255348.218	324.174
NVA-51	170069.926	248492.037	166.715
NVA-52	169770.935	242841.299	237.884
NVA-53	159842.809	238093.780	658.329
NVA-54	181091.899	236099.764	884.306
NVA-55	179529.201	225353.310	191.063
NVA-56	180406.013	216938.686	3.159
NVA-57	191004.761	218228.550	8.293
NVA-58	192973.836	227365.361	75.007
NVA-59	175453.194	233348.171	579.594
NVA-60	183553.402	242694.632	439.892
NVA-61	182565.201	250405.538	457.149
NVA-62	185212.626	257531.255	187.214
NVA-63	188375.998	266902.846	17.886
NVA-64	184659.967	272023.745	3.229
NVA-65	196538.944	268075.613	25.801
NVA-66	195648.307	258665.892	104.429
NVA-67	192802.209	250967.217	408.447
NVA-68	204833.476	232271.070	577.564
NVA-69	191999.373	236236.027	804.265
NVA-70	197473.857	224621.735	137.466
NVA-71	202210.811	215209.506	10.414
NVA-72	207581.266	222986.349	124.090
NVA-73	213951.003	234592.460	659.172
NVA-74	204359.563	243164.708	516.334
NVA-75	204078.907	248740.950	609.819
NVA-76	205159.111	261040.823	145.771
NVA-77	209284.181	269479.703	9.480
NVA-78	218928.884	263940.818	10.537
NVA-79	220515.547	251571.675	100.242
NVA-80	218136.454	245800.461	649.988
NVA-81	228980.153	239173.291	471.920
NVA-82	222849.996	226309.054	463.569
NVA-83	219615.764	218667.049	44.006
NVA-84	235473.520	216003.038	27.124
NVA-86	234447.713	234472.327	401.197

NVA-87	244015.751	237651.704	376.620
NVA-88	233935.022	258408.991	31.114
NVA-89	238414.390	262973.323	16.574
NVA-90	248675.579	264586.656	3.113
NVA-91	257537.402	256050.798	44.664
NVA-92	254310.070	245317.464	56.910
NVA-93	250744.652	238635.710	100.807
NVA-94	255668.162	224924.889	24.350
NVA-95	252712.551	220850.497	45.976
NVA-96	264434.370	230133.945	30.429
NVA-97	264239.756	235488.173	20.257
NVA-98	263329.934	242743.599	97.058
NVA-99	273532.537	242367.908	21.585
NVA-100	283179.357	247711.563	20.105
NVA-101	282850.346	253507.245	10.512
NVA-102	274816.592	260409.466	6.017
NVA-103	262892.679	265435.220	1.661
NVA-104	261962.081	260615.786	8.532
NVA-105	298218.466	233439.132	1.741
NVA-106	303581.238	234337.874	21.612
NVA-107	300361.169	229328.939	7.877
NVA-108	321076.748	250926.844	20.100
NVA-109	319349.083	253321.489	3.867
NVA-110	322384.381	252253.928	3.266
NVA-111	161912.197	240308.938	486.318
NVA-112	181930.855	215241.338	2.377
NVA-113	155430.011	247651.308	523.731
NVA-114	147596.230	215464.010	5.271
NVA-115	153113.992	253087.345	382.868
NVA-116	144386.488	226240.491	85.726
NVA-117	150620.168	251912.584	373.976
NVA-118	135327.479	229612.483	41.407
NVA-119	145684.907	255426.456	288.812
NVA-120	129543.468	232761.553	31.687
NVA-121	141410.080	256244.172	80.673
NVA-122	119859.086	227581.776	5.474
NVA-123	139200.561	257154.484	67.232
NVA-124	121545.361	237841.003	1.406
NVA-125	126608.800	257992.704	178.781
NVA-126	123096.046	248099.278	3.476
NVA-128	124501.856	272232.749	77.358
NVA-130	126800.340	269017.495	126.102

VVA-01	319494.664	254839.686	133.840
VVA-02	323422.286	252632.210	56.464
VVA-03	320855.319	253557.969	6.842
VVA-04	317591.913	255155.577	2.126
VVA-05	320061.544	252180.723	7.965
VVA-06	299330.083	229627.269	27.732
VVA-07	311955.683	230682.104	6.772
VVA-08	304974.461	234123.088	43.320
VVA-09	299690.632	230831.694	77.463
VVA-10	280811.034	256955.730	15.727
VVA-11	277248.052	250398.489	83.147
VVA-12	278085.169	242642.687	3.828
VVA-13	266049.279	226675.299	84.893
VVA-14	260360.814	223368.707	16.143
VVA-15	251324.028	234747.660	285.449
VVA-16	257612.290	241416.211	151.989
VVA-17	261995.309	251502.284	532.492
VVA-18	266859.395	258765.311	31.146
VVA-19	255578.964	261604.512	5.567
VVA-20	247267.768	252827.996	211.214
VVA-21	254462.004	250547.212	144.247
VVA-22	239733.421	243404.427	97.145
VVA-23	244180.877	230424.041	545.988
VVA-24	244742.094	218423.030	11.344
VVA-25	233791.089	218278.692	80.550
VVA-26	235225.735	238242.538	382.628
VVA-27	234989.344	248642.722	426.939
VVA-28	241762.023	259564.622	44.233
VVA-29	223172.116	258325.135	53.624
VVA-30	225807.387	249212.741	413.754
VVA-31	221296.097	241869.080	204.476
VVA-32	227542.068	229142.000	522.277
VVA-33	222171.338	222989.362	212.948
VVA-34	215853.750	217134.547	17.831
VVA-35	201705.552	220384.112	50.922
VVA-36	211178.837	229655.046	278.659
VVA-37	220550.275	234666.052	386.220
VVA-38	210394.862	247012.566	621.085
VVA-39	209262.166	256077.078	124.690
VVA-40	195957.846	265181.097	77.934
VVA-41	198913.950	252455.723	71.666
VVA-42	201238.900	237419.404	859.602

VVA-43	196067.577	231830.452	354.310
VVA-44	185534.944	218998.062	4.067
VVA-45	175270.817	224034.380	79.869
VVA-46	194308.233	243524.249	663.463
VVA-47	183234.054	254723.380	233.016
VVA-48	182537.027	263205.205	150.766
VVA-49	176528.311	268245.896	14.325
VVA-50	174272.965	257135.631	125.684
VVA-51	175920.912	245897.730	264.027
VVA-52	172950.634	234856.436	765.859
VVA-53	183656.815	237228.707	1158.672
VVA-54	165479.721	220903.836	13.048
VVA-55	162172.702	232080.177	629.532
VVA-56	158611.483	235839.903	730.646
VVA-57	162979.960	248070.836	632.870
VVA-58	163684.273	256324.209	300.710
VVA-59	168339.493	264704.921	126.857
VVA-60	154818.418	265748.082	162.055
VVA-61	153693.460	251566.632	306.997
VVA-62	157143.806	245283.716	567.356
VVA-63	144566.116	229394.929	225.620
VVA-64	152999.646	212985.081	0.267
VVA-65	144181.902	217315.097	15.605
VVA-66	144477.608	226189.035	86.302
VVA-67	130816.222	239751.886	188.686
VVA-68	136367.595	240442.863	321.816
VVA-69	144756.862	251570.250	201.950
VVA-70	143975.933	257027.100	295.522
VVA-71	147810.452	265926.244	196.409
VVA-72	142682.005	271518.712	83.382
VVA-73	130378.930	272616.132	58.688
VVA-74	136510.158	267198.661	188.381
VVA-75	128077.180	263734.154	198.625
VVA-76	118779.396	258931.917	66.248
VVA-77	132187.016	259812.754	89.050
VVA-78	133730.314	253587.329	187.050
VVA-79	125171.198	251138.096	11.750
VVA-80	130399.198	246201.051	268.572
VVA-81	134626.475	239948.891	348.695
VVA-82	129487.178	230310.539	19.077
VVA-83	124887.961	218969.726	7.322
VVA-84	138192.875	226536.944	63.891

VVA-85	133040.845	219592.509	15.638

Table 5 – Vertical Accuracy Check Point Coordinates.

One (1) checkpoint (NVA-85) was removed from the vertical accuracy testing for the classified lidar due to the location. As discussed in the raw swath vertical accuracy testing section of this report, this point was located within the data void found in the southeast region of Puerto Rico's mainland. For further information on this data void, see the *Data Void* section of this report.

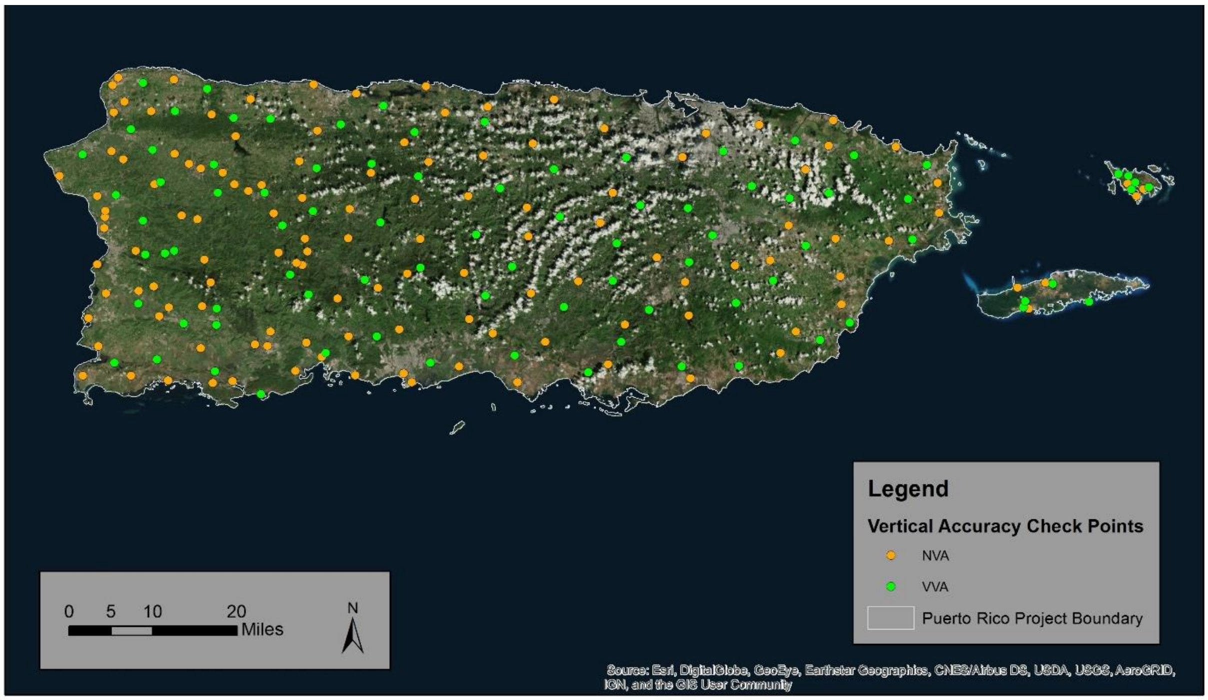


Figure 26 – Distribution of Vertical Accuracy Check Points.

VERTICAL ACCURACY TEST PROCEDURES

NVA (Non-vegetated Vertical Accuracy) is determined with check points located only in non-vegetated terrain, including open terrain (grass, dirt, sand, and/or rocks) and urban areas, where there is a very high probability that the lidar sensor will have detected the bare-earth ground surface and where random errors are expected to follow a normal error distribution. The NVA determines how well the calibrated lidar sensor performed. With a normal error distribution, the vertical accuracy at the 95% confidence level is computed as the vertical root mean square error ($RMSE_z$) of the checkpoints x 1.9600. For the Puerto Rico QL2 Lidar Project, vertical accuracy must be 19.6 cm or less based on an $RMSE_z$ of 10 cm x 1.9600.

VVA (Vegetated Vertical Accuracy) is determined with all checkpoints in vegetated land cover categories, including tall grass, weeds, crops, brush and low trees, and fully forested areas, where there is a possibility that the lidar sensor and post-processing may yield elevation errors that do not follow a normal error distribution. VVA at the 95% confidence level equals the 95^{th} percentile error for all checkpoints in all vegetated land cover categories combined. The USGS Puerto Rico

QL2 Lidar project VVA standard is 29.4 cm based on the 95th percentile. The VVA is accompanied by a listing of the 5% outliers that are larger than the 95th percentile used to compute the VVA; these are always the largest outliers that may depart from a normal error distribution. Here, $Accuracy_z$ differs from VVA because $Accuracy_z$ assumes elevation errors follow a normal error distribution where RMSE procedures are valid, whereas VVA assumes lidar errors may not follow a normal error distribution in vegetated categories, making the RMSE process invalid.

The relevant testing criteria are summarized in Table 6.

Quantitative Criteria	Measure of Acceptability
Non-Vegetated Vertical Accuracy (NVA) in open terrain and urban land cover categories using $RMSE_z$ *1.9600	19.6 cm (based on $RMSE_z$ (10 cm) * 1.9600)
Vegetated Vertical Accuracy (VVA) in all vegetated land cover categories combined at the 95% confidence level	29.4 cm (based on 95th percentile)

Table 6 — Acceptance Criteria

The primary QA/QC vertical accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications.
2. Next, Dewberry interpolated the bare-earth lidar DTM to provide the z-value for every checkpoint.
3. Dewberry then computed the associated z-value differences between the interpolated z-value from the lidar data and the ground truth survey checkpoints and computed NVA, VVA, and other statistics.
4. The data were analyzed by Dewberry to assess the accuracy of the data. The review process examined the various accuracy parameters as defined by the scope of work. The overall descriptive statistics of each dataset were computed to assess any trends or anomalies. This report provides tables, graphs and figures to summarize and illustrate data quality.

VERTICAL ACCURACY RESULTS

The table below summarizes the tested vertical accuracy resulting from a comparison of the surveyed checkpoints to the elevation values present within the fully classified lidar LAS files.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm
NVA	127	18.2	
VVA	85		20.6

Table 7 — Tested NVA and VVA

This lidar dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be $RMSE_z$ =9.3 cm, equating to +/- 18.2 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 20.6 cm at the 95th percentile.

The figure below illustrates the magnitude of the differences between the QA/QC checkpoints and lidar data. This shows that the majority of lidar elevations were within +/- 10 cm of the checkpoints elevations, but there were some outliers where lidar and checkpoint elevations differed by up to +50 cm.

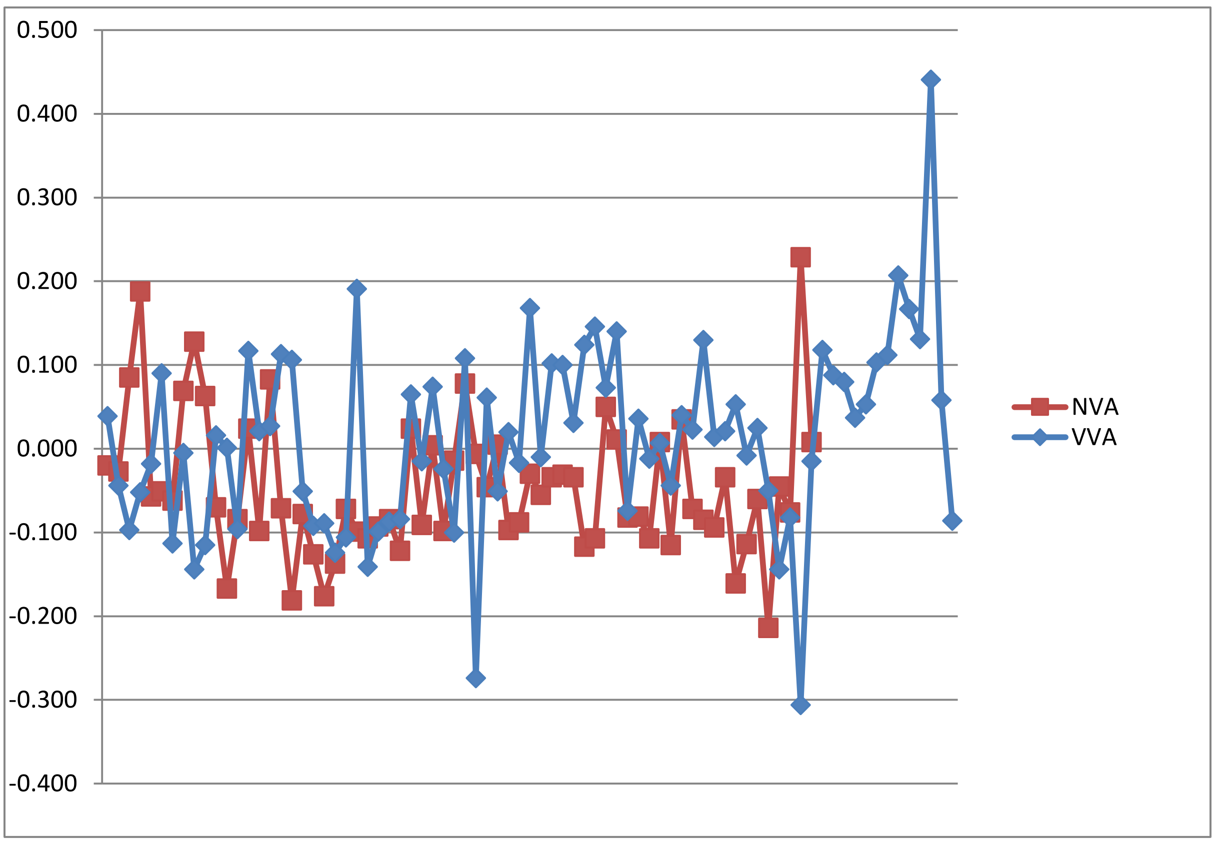


Figure 27– Magnitude of elevation discrepancies (in meters) per land cover category

Table 8 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83 (2011) Puerto Rico State Plane		PRVD02 (Geoid 12B)	Lidar Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			

VVA-04	317591.913	255155.577	2.126	1.820	-0.306	0.306
VVA-13	266049.279	226675.299	84.893	85.100	0.207	0.207
VVA-16	257612.290	241416.211	151.989	152.430	0.441	0.441
VVA-26	235225.735	238242.538	382.628	382.990	0.362	0.362
VVA-32	227542.068	229142.000	522.277	522.730	0.453	0.453

Table 8 — 5% Outliers

Table 9 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	127	0.093	-0.023	-0.034	0.337	0.090	0.035	-0.274	0.229
VVA	85	N/A	0.019	0.000	0.740	0.127	2.189	-0.306	0.453

Table 9 — Overall Descriptive Statistics

The figure below illustrates a histogram of the associated elevation discrepancies between the QA/QC checkpoints and elevations interpolated from the lidar triangulated irregular network (TIN). The frequency shows the number of discrepancies within each band of elevation differences. Although the discrepancies vary between a low of -0.2 meters and a high of +0.2 meters, the histogram shows that the majority of the discrepancies are skewed on the positive side. The vast majority of points are within the ranges of -0.2 meters to +0.1 meters.

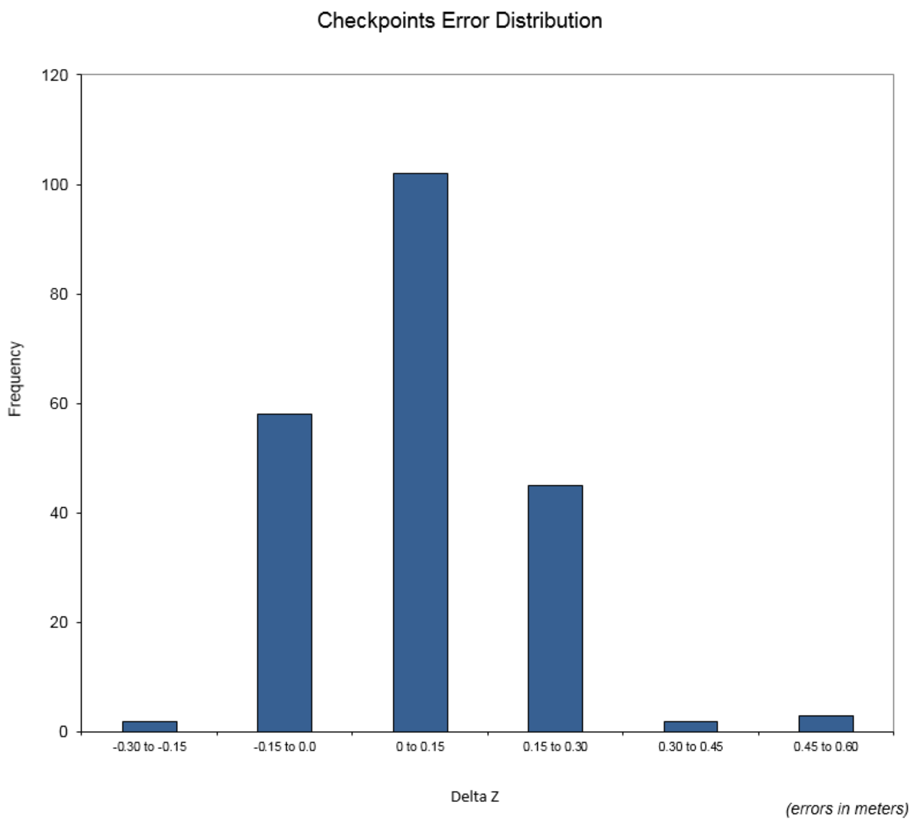


Figure 28 — Histogram of Elevation Discrepancies with errors in meters

Based on the vertical accuracy testing conducted by Dewberry, the lidar dataset for the Puerto Rico QL2 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

HORIZONTAL ACCURACY TEST PROCEDURES

Horizontal accuracy testing requires well-defined checkpoints that can be identified in the dataset. Elevation datasets, including lidar datasets, do not always contain well-defined checkpoints suitable for horizontal accuracy assessment. However, the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) recommends at least half of the NVA vertical check points should be located at the ends of paint stripes or other point features visible on the lidar intensity image, allowing them to double as horizontal check points.

Dewberry reviews all NVA checkpoints to determine which, if any, of these checkpoints are located on photo-identifiable features in the intensity imagery. This subset of checkpoints are then used for horizontal accuracy testing.

The primary QA/QC horizontal accuracy testing steps used by Dewberry are summarized as follows:

1. Dewberry's team surveyed QA/QC vertical checkpoints in accordance with the project's specifications and tried to locate half of the NVA checkpoints on features photo-identifiable in the intensity imagery.

2. Next, Dewberry identified the well-defined features in the intensity imagery.
3. Dewberry then computed the associated xy-value differences between the coordinates of the well-defined feature in the lidar intensity imagery and the ground truth survey checkpoints.
4. The data were analyzed by Dewberry to assess the accuracy of the data. Horizontal accuracy was assessed using NSSDA methodology where horizontal accuracy is calculated at the 95% confidence level. This report provides the results of the horizontal accuracy testing.

HORIZONTAL ACCURACY RESULTS

Three checkpoints were determined to be photo-identifiable in the intensity imagery and were used to test the horizontal accuracy of the lidar dataset. As only three (3) checkpoints were photo-identifiable, the results are not statistically significant enough to report as a final tested value, but the results of the testing are still shown in the Table below.

Using NSSDA methodology (endorsed by the ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014)), horizontal accuracy at the 95% confidence level (called ACCURACYr) is computed by the formula RMSEr * 1.7308 or RMSExy * 2.448.

No horizontal accuracy requirements or thresholds were provided for this project. However, lidar datasets are generally calibrated by methods designed to ensure a horizontal accuracy of 1 meter or less at the 95% confidence level.

# of Points	$RMSE_x$ (Target=41 cm)	$RMSE_y$ (Target=41 cm)	$RMSE_r$ (Target=58 cm)	$ACCURACY_r$ ($RMSE_r$ x 1.7308) Target=100 cm
3	7.9	9.7	12.5	21.6

Table 10-Tested horizontal accuracy at the 95% confidence level

This data set was produced to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 41 cm RMSEx/RMSEy Horizontal Accuracy Class which equates to Positional Horizontal Accuracy = +/- 1 meter at a 95% confidence level. Three (3) checkpoints were photo-identifiable but do not produce a statistically significant tested horizontal accuracy value. Using this small sample set of photo-identifiable checkpoints, positional accuracy of this dataset was found to be RMSEx = 7.9 cm and RMSEy = 9.7 cm which equates to +/- 21.6 cm at 95% confidence level. While not statistically significant, the results of the small sample set of checkpoints are within the produced to meet horizontal accuracy.

Breakline Production & Qualitative Assessment Report

BREAKLINE PRODUCTION METHODOLOGY

Dewberry used a combination of lidargrammetry and automated techniques to collect breaklines for this project. The delineation of lakes and ponds and tidal waters, or other water bodies at a constant elevation, was achieved using eCognition software. Dewberry produced full point cloud intensity imagery, bare earth ground models, density models, and slope models. These files were ingested into eCognition, segmented into polygons, and training samples were created to identify water. eCognition used the training samples and defined parameters to identify water segments throughout the project area. Water segments were then reviewed for completeness. Segments identified as lakes and ponds or tidal waters were merged and smoothed. 3D elevations were then applied to the breakline features. Lidargrammetry was used to monotonically collect streams and rivers, or features that have gradient 3D elevations. Dewberry used GeoCue software to develop lidar stereo models of the project area so the lidar derived data could be viewed in 3-D stereo using Socet Set softcopy photogrammetric software. Using lidargrammetry procedures with lidar intensity imagery, Dewberry used the stereo models to stereo-compile the streams and rivers in accordance with the project's Data Dictionary.

All drainage breaklines are monotonically enforced to show downhill flow. Water bodies are at a constant elevation where the lowest elevation of the water body has been applied to the entire water body.

BREAKLINE QUALITATIVE ASSESSMENT

Dewberry completed breakline qualitative assessments according to a defined workflow. The following workflow diagram shown in Figure 28 represents the steps taken by Dewberry to provide a thorough qualitative assessment of the breakline data.

Completeness and horizontal placement is verified through visual reviews against lidar intensity imagery. Automated checks are applied on all breakline features to validate topology, including the 3D connectivity of features, enforced monotonicity on linear hydrographic breaklines, and flatness on water bodies.

The next step is to compare the elevation of the breakline vertices against the ground elevation extracted from the ESRI Terrain built from the lidar ground points, keeping in mind that a discrepancy is expected because of the hydro-enforcement applied to the breaklines and because of the interpolated imagery used to acquire the breaklines. A given tolerance is used to validate if the elevations differ too much from the lidar.

After all corrections and edits to the breakline features, the breaklines are imported into the final GDB and verified for correct formatting.

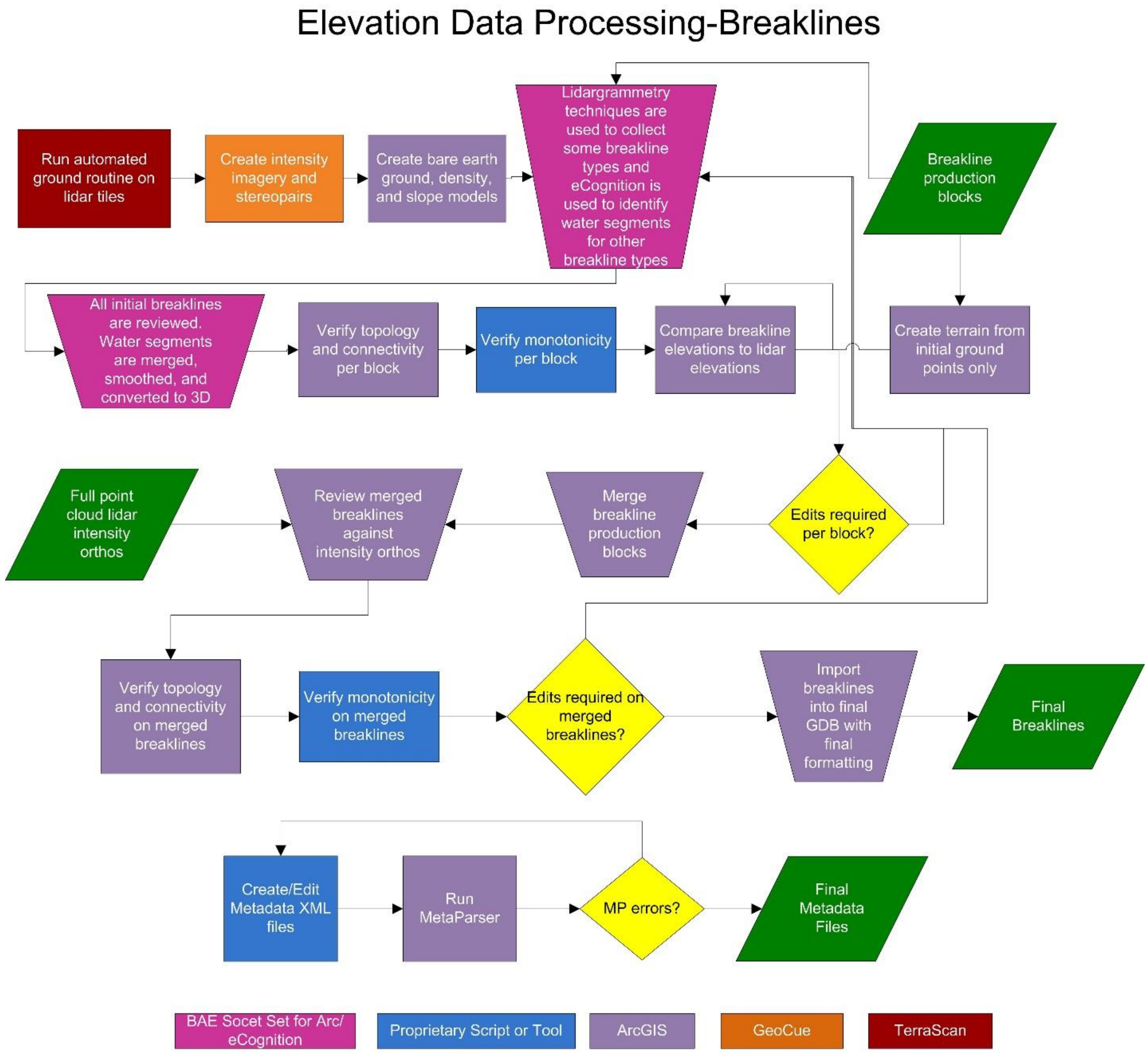


Figure 29-Breakline QA/QC workflow

BREAKLINE CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Use lidar-derived data, which may include intensity imagery, stereo pairs, bare earth ground models, density models, slope models, and terrains, to collect breaklines according to project specifications.
Pass	In areas of heavy vegetation or where the exact shoreline is hard to delineate, it is better to err on placing the breakline *slightly* inside or seaward of the shoreline (breakline can be inside shoreline by 1x-2x NPS).

Pass	After each producer finishes breakline collection for a block, each producer must perform a completeness check, breakline variance check, and all automated checks on their block before calling that block complete and ready for the final merge and QC
Pass	After breaklines are completed for production blocks, all production blocks should be merged together and completeness and automated checks should be performed on the final, merged GDB. Ensure correct snapping-horizontal (x,y) and vertical (z)-between all production blocks.
Pass	Check entire dataset for missing features that were not captured, but should be to meet baseline specifications or for consistency. Features should be collected consistently across tile bounds. Check that the horizontal placement of breaklines is correct. Breaklines should be compared to full point cloud intensity imagery and terrains
Pass	Breaklines are correctly edge-matched to adjoining datasets in completion, coding, and horizontal placement.
Pass	Using a terrain created from lidar ground (all ground including 2, 8, and 10) and water points (class 9), compare breakline Z values to interpolated lidar elevations.
Pass	Perform all Topology and Data Integrity Checks
Pass	Perform hydro-flattening and hydro-enforcement checks including monotonicity and flatness from bank to bank on linear hydrographic features and flatness of water bodies. Tidal waters should preserve as much ground as possible and can include variations or be non-monotonic.

Table 11-A subset of the high-level steps from Dewberry's Production and QA/QC checklist performed for this project.

DATA DICTIONARY

The following data dictionary was used for this project.

Horizontal and Vertical Datum

The horizontal datum shall be North American Datum of 1983, 2011 adjustment (NAD83 2011), Units in Meters. The vertical datum shall be referenced to the Puerto Rico Vertical Datum of 2002, Units in Meters. Geoid12B shall be used to convert ellipsoidal heights to orthometric heights.

Coordinate System and Projection

All data shall be projected to State Plane Puerto Rico Zone 5200, Horizontal Units in Meters and Vertical Units in Meters.

Inland Streams and Rivers

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: STREAMS_AND_RIVERS
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict linear hydrographic features with a width greater than 100 feet.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software

SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Streams and Rivers	Linear hydrographic features such as streams, rivers, canals, etc. with an average width greater than 100 feet. In the case of embankments, if the feature forms a natural dual line channel, then capture it consistent with the capture rules. Other natural or manmade embankments will not qualify for this project.	Capture features showing dual line (one on each side of the feature). Average width shall be greater than 100 feet to show as a double line. Each vertex placed should maintain vertical integrity. Generally both banks shall be collected to show consistent downhill flow. There are exceptions to this rule where a small branch or offshoot of the stream or river is present. The banks of the stream must be captured at the same elevation to ensure flatness of the water feature. If the elevation of the banks appears to be different see the task manager or PM for further guidance. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Every effort should be made to avoid breaking a stream or river into segments. Dual line features shall break at road crossings (culverts). In areas where a bridge is present the dual line feature shall continue through the bridge. Islands: The double line stream shall be captured around an island if the island is greater than 1 acre. In this case a segmented polygon shall be used around the island in order to allow for the island feature to remain as a "hole" in the feature.

Inland Ponds and Lakes

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: PONDS_AND_LAKES
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will depict closed water body features that are at a constant elevation.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Ponds and Lakes	Land/Water boundaries of constant elevation water bodies such as lakes, reservoirs, ponds, etc. Features shall be defined as closed polygons and contain an elevation value that reflects the best estimate of the water elevation at the time of data capture. Water body features will be captured for features 2 acres in size or greater. "Donuts" will exist where there are islands within a closed water body feature.	Water bodies shall be captured as closed polygons with the water feature to the right. The compiler shall take care to ensure that the z-value remains consistent for all vertices placed on the water body. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. An Island within a Closed Water Body Feature that is 1 acre in size or greater will also have a "donut polygon" compiled. These instructions are only for docks or piers that follow the coastline or water's edge, not for docks or piers that extend perpendicular from the land into the water. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the

		water where it can be directly measured. If there is no clear indication of the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water.

Tidal Waters

Feature Dataset: BREAKLINES
Feature Type: Polygon
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: TIDAL_WATERS
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polygon feature class will outline the land / water interface at the time of lidar acquisition.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software
SHAPE_AREA	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
TIDAL_WATERS	The coastal breakline will delineate the land water interface using lidar data as reference. In flight line boundary areas with tidal variation the coastal shoreline may show stair stepping as no feathering is allowed. Stair stepping is allowed to show as much ground as the collected data permits.	The feature shall be extracted at the apparent land/water interface, as determined by the lidar intensity data, to the extent of the tile boundaries. Differences caused by tidal variation are acceptable and breaklines delineated should reflect that change with no feathering. Breaklines must be captured at or just below the elevations of the immediately surrounding terrain. Under no circumstances should a feature be elevated above the surrounding lidar points. Acceptable variance in the negative direction will be defined for each project individually. If it can be reasonably determined where the edge of water most probably falls, beneath the dock or pier, then the edge of water will be collected at the elevation of the water where it can be directly measured. If there is a clearly-indicated headwall or bulkhead adjacent to the dock or pier and it is evident that the waterline is most probably adjacent to the headwall or bulkhead, then the water line will follow the headwall or bulkhead at the elevation of the water where it can be directly measured. If there is no clear indication of

		the location of the water's edge beneath the dock or pier, then the edge of water will follow the outer edge of the dock or pier as it is adjacent to the water, at the measured elevation of the water. Breaklines shall snap and merge seamlessly with linear hydrographic features.

Beneath Bridge Breaklines

Feature Dataset: BREAKLINES
Feature Type: Polyline
Contains Z Values: Yes
XY Resolution: Accept Default Setting
XY Tolerance: 0.003

Feature Class: Bridge_Breaklines
Contains M Values: No
Annotation Subclass: None
Z Resolution: Accept Default Setting
Z Tolerance: 0.001

Description

This polyline feature class is used to enforce terrain beneath bridge decks where ground data may not have been acquired. Enforcing the terrain beneath bridge decks prevents bridge saddles.

Table Definition

Field Name	Data Type	Allow Null Values	Default Value	Domain	Precision	Scale	Length	Responsibility
OBJECTID	Object ID							Assigned by Software
SHAPE	Geometry							Assigned by Software
SHAPE_LENGTH	Double	Yes			0	0		Calculated by Software

Feature Definition

Description	Definition	Capture Rules
Bridge Breaklines	Bridge Breaklines should be used where necessary to enforce terrain beneath bridge decks and to prevent bridge saddles in the bare earth DEMs.	Bridge breaklines should be collected beneath bridges where bridge saddles exist or are likely to exist in the bare earth DEMs. Bridge breaklines should be collected perpendicular to the bridge deck so that the endpoints are on either side of the bridge deck. Typically two bridge breaklines are collected per bridge deck, one at either end of the bridge deck to enforce the terrain under the full bridge deck. The endpoints of the bridge breaklines will match the elevation of the ground at their xy position to enforce the ground/bare earth elevations beneath the bridge deck and prevent bridge saddles from forming.

DEM Production & Qualitative Assessment

DEM PRODUCTION METHODOLOGY

Dewberry utilized ESRI software and Global Mapper for the DEM production and QC process. ArcGIS software is used to generate the products and the QC is performed in both ArcGIS and Global Mapper. The figure below shows the entire process necessary for bare earth DEM production, starting from the lidar swath processing.

The final bare-earth lidar points are used to create a terrain. The final 3D breaklines collected for the project are also enforced in the terrain. The terrain is then converted to raster format using linear interpolation. For most projects, a single terrain/DEM can be created for the whole project. For very large projects, multiple terrains/DEMs may be created. The DEM(s) is reviewed for any issues requiring corrections, including remaining lidar mis-classifications, erroneous breakline elevations, poor hydro-flattening or hydro-enforcement, and processing artifacts. After corrections are applied, the DEM(s) is then split into individual tiles following the project tiling scheme. The tiles are verified for final formatting and then loaded into Global Mapper to ensure no missing or corrupt tiles and to ensure seamlessness across tile boundaries.

Figure 30-DEM Production Workflow

DEM QUALITATIVE ASSESSMENT

Dewberry performed a comprehensive qualitative assessment of the bare earth DEM deliverables to ensure that all tiled DEM products were delivered with the proper extents, were free of processing artifacts, and contained the proper referencing information. This process was performed in ArcGIS software with the use of a tool set Dewberry has developed to verify that the raster extents match those of the tile grid and contain the correct projection information. The DEM data was reviewed at a scale of 1:5000 to review for artifacts caused by the DEM generation process and to review the hydro-flattened features. To perform this review Dewberry creates HillShade models and overlays a partially transparent colorized elevation model to review for these issues. All corrections are completed using Dewberry's proprietary correction workflow. Upon completion of the corrections, the DEM data is loaded into Global Mapper for its second review and to verify corrections. Once the DEMs are tiled out, the final tiles are again loaded into Global Mapper to ensure coverage, extents, and that the final tiles are seamless.

The images below show an example of a bare earth DEM.

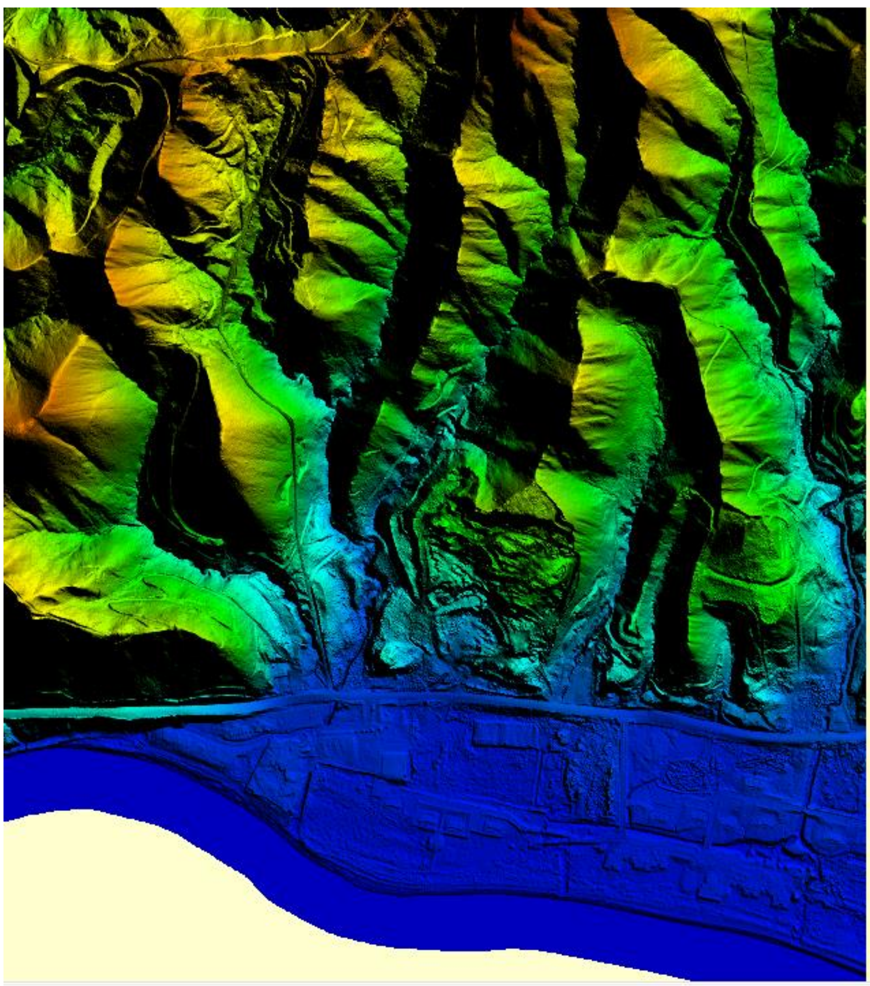


Figure 31-Tile 19QFA17505100. Bare Earth DEM

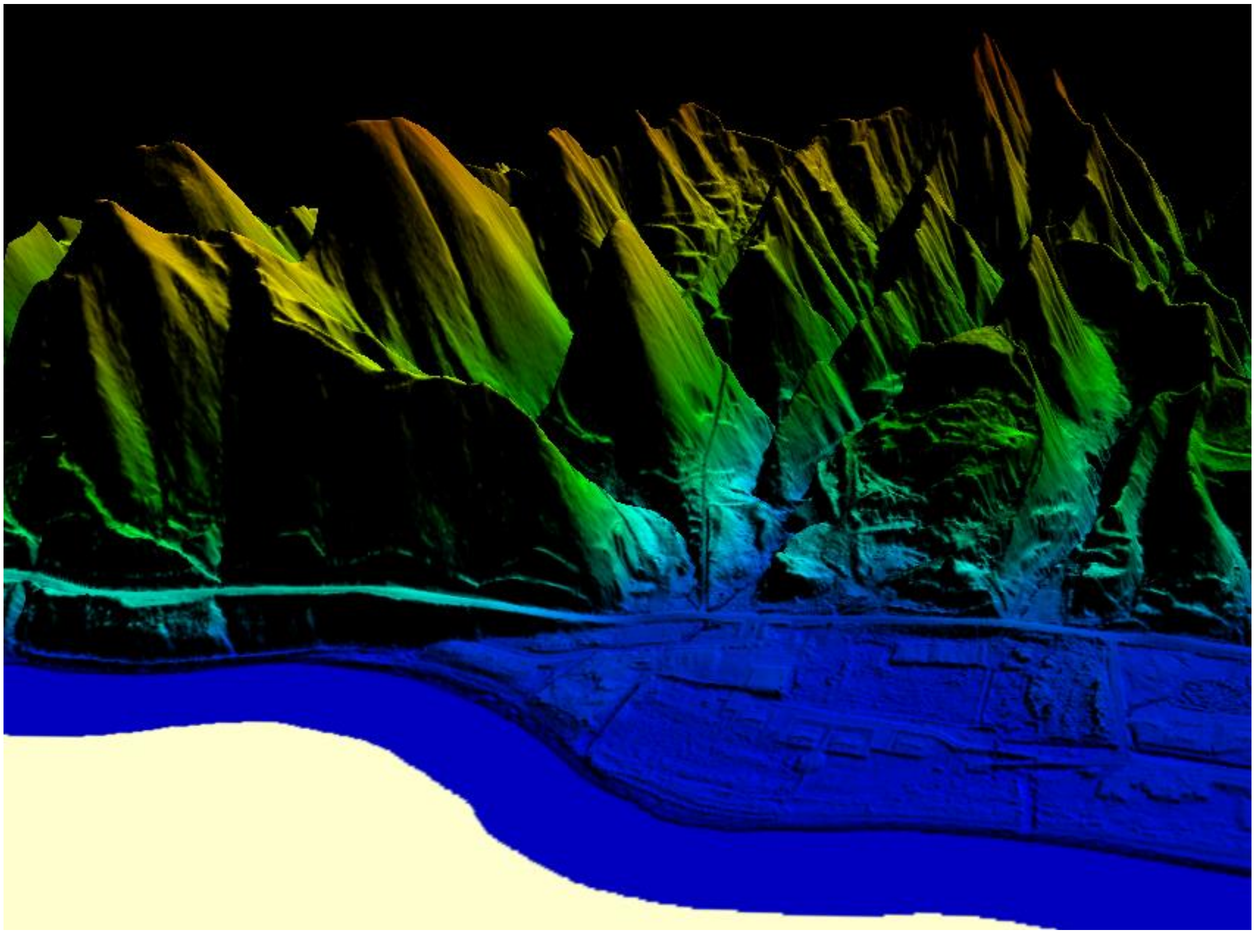


Figure 32- Tile 19QFA17505100. 3D Profile view of the bare earth DEM

When some bridges are removed from the ground surface, the distance from bridge abutment to bridge abutment is small enough that the DEM interpolates across the entire bridge opening, forming 'bridge saddles.' Dewberry collected 3D bridge breaklines in locations where bridge saddles were present and enforced these breaklines in the final DEM creation to help mitigate the bridge saddle artifacts. The image below on the left shows a bridge saddle while the image below on the right shows the same bridge after bridge breaklines have been enforced.

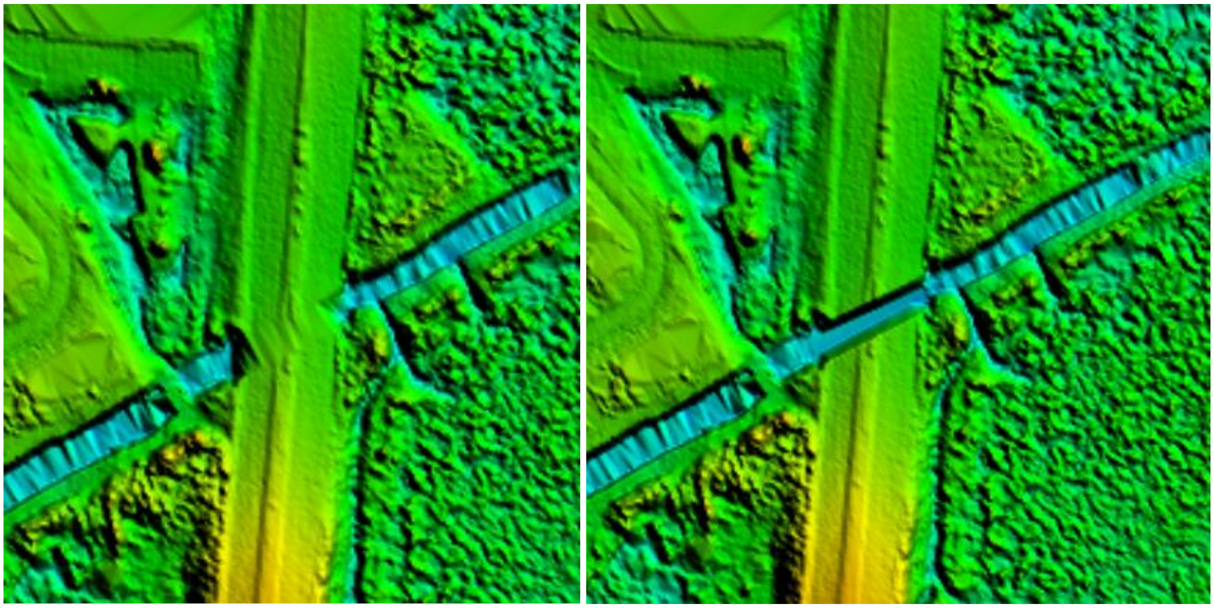


Figure 33-Tile 19QFA23503900. The DEM on the left shows a bridge saddle artifact while the DEM on the right shows the same location after bridge breaklines have been enforced.

DEM VERTICAL ACCURACY RESULTS

The same two hundred twelve (212) checkpoints that were used to test the vertical accuracy of the lidar were used to validate the vertical accuracy of the final DEM products as well. Accuracy results may vary between the source lidar and final DEM deliverable. DEMs are created by averaging several lidar points within each pixel which may result in slightly different elevation values at each survey checkpoint when compared to the source LAS, which does not average several lidar points together but may interpolate (linearly) between two or three points to derive an elevation value. The vertical accuracy of the DEM is tested by extracting the elevation of the pixel that contains the x/y coordinates of the checkpoint and comparing these DEM elevations to the surveyed elevations. Dewberry typically uses LP360 software to test the swath lidar vertical accuracy, Terrascan software to test the classified lidar vertical accuracy, and Esri ArcMap to test the DEM vertical accuracy so that three different software programs are used to validate the vertical accuracy for each project.

Table 12 summarizes the tested vertical accuracy results from a comparison of the surveyed checkpoints to the elevation values present within the final DEM dataset.

Land Cover Category	# of Points	NVA — Non-vegetated Vertical Accuracy ($RMSE_z$ x 1.9600) Spec=19.6 cm	VVA — Vegetated Vertical Accuracy (95th Percentile) Spec=29.4 cm
NVA	127	18.5	
VVA	85		23.1

Table 12 — DEM tested NVA and VVA

This DEM dataset was tested to meet ASPRS Positional Accuracy Standards for Digital Geospatial Data (2014) for a 10 cm RMSEz Vertical Accuracy Class. Actual NVA accuracy was found to be

$RMSE_z$ =9.4 cm, equating to +/- 18.5 cm at 95% confidence level. Actual VVA accuracy was found to be +/- 23.1 cm at the 95th percentile.

Table 13 lists the 5% outliers that are larger than the VVA 95th percentile.

Point ID	NAD83 (2011) Puerto Rico State Plane		PRVD02 (Geoid 12B)	DEM Z (m)	Delta Z	AbsDeltaZ
	Easting X (m)	Northing Y (m)	Survey Z (m)			
VVA-04	317591.913	255155.577	2.126	1.790	-0.336	0.366
VVA-13	266049.279	226675.299	84.893	85.130	0.237	0.237
VVA-16	257612.290	241416.211	151.989	152.457	0.468	0.468
VVA-26	235225.735	238242.538	382.628	383.036	0.408	0.408
VVA-32	227542.068	229142.000	522.277	522.818	0.541	0.541

Table 13 — 5% Outliers

Table 14 provides overall descriptive statistics.

100 % of Totals	# of Points	RMSEz (m) NVA Spec=0.1 m	Mean (m)	Median (m)	Skew	Std Dev (m)	Kurtosis	Min (m)	Max (m)
NVA	127	0.094	-0.022	-0.026	0.167	0.092	0.193	-0.264	0.224
VVA	85	N/A	0.016	0.016	1.085	0.136	3.438	-0.336	0.541

Table 14 — Overall Descriptive Statistics

Based on the vertical accuracy testing conducted by Dewberry, the DEM dataset for the USGS Puerto Rico QL2 Lidar Project satisfies the project's pre-defined vertical accuracy criteria.

DEM CHECKLIST

The following table represents a portion of the high-level steps in Dewberry's bare earth DEM Production and QA/QC checklist that were performed for this project.

Pass/Fail	Validation Step
Pass	Masspoints (LAS to multipoint) are created from ground points only (class 2 and class 8 if model key points created, but no class 10 ignored ground points or class 9 water points
Pass	Create a terrain for each production block using the final bare earth lidar points and final breaklines.
Pass	Convert terrains to rasters using project specifications for grid type, formatting, and cell size
Pass	Create hillshades for all DEMs
Pass	Manually review bare-earth DEMs in ArcMap with hillshades to check for issues
Pass	DEMs should be hydro-flattened or hydro-enforced as required by project specifications
Pass	DEMs should be seamless across tile boundaries

Pass	Water should be flowing downhill without excessive water artifacts present
Pass	Water features should NOT be floating above surrounding
Pass	Bridges should NOT be present in bare-earth DEMs.
Pass	Any remaining bridge saddles where below bridge breaklines were not used need to be fixed by adding below bridge breaklines and re-processing.
Pass	All qualitative issues present in the DEMs as a result of lidar processing and editing issues must be marked for corrections in the lidar These DEMs will need to be recreated after the lidar has been corrected.
Pass	Calculate DEM Vertical Accuracy including NVA, VVA, and other statistics
Pass	Split the DEMs into tiles according to the project tiling scheme
Pass	Verify all properties of the tiled DEMs, including coordinate reference system information, cell size, cell extents, and that compression has not been applied to the tiled DEMs
Pass	Load all tiled DEMs into Global Mapper to verify complete coverage to the (buffered) project boundary and that no tiles are corrupt.

Table 15-A subset of the high-level steps from Dewberry's bare earth DEM Production and QA/QC checklist performed for this project.

Appendix A: Accuracy Check Point Survey Report

Please see the separate document delivered with this report:
Appendix_A_Puerto_Rico_Lidar_Accuracy_Check_Point_Survey_Report.pdf

Appendix B: Ground Control Survey Report

Please see the separate document delivered with this report:
Appendix_B_Puerto_Rico_Lidar_Ground_Control_Survey_Report.pdf

Appendix C: Complete List of Delivered Tiles

19QFV19000900	19QGA70004050	19QHA45005850	19QGA38507500	19QGV85001800	20QKF70504050
19QFV20500900	19QGA71504050	20QJF46505850	19QGA40007500	19QGV85001950	20QKF70504200
19QGV41500900	19QGA73004050	20QJF48005850	19QGA00002700	19QGV85002100	20QKF70504350
19QGV43000900	19QGA74504050	20QJF49505850	19QGA00002850	19QGV85002250	20QKF70504500
19QGV44500900	19QGA76004050	20QJF51005850	19QGA00003000	19QGV85002400	20QKF70504650
19QGV46000900	19QGA77504050	20QJF52505850	19QGA00003150	19QGV85002550	20QKF70504800
19QGV47500900	19QGA79004050	20QJF54005850	19QGA00003300	19QGV86501350	20QKF70504950
19QGV49000900	19QGA80504050	19QFA87506000	19QGA00003450	19QGV86501500	20QKF70505100
19QFV17501050	19QFA20504200	19QFA89006000	19QGA00003600	19QGV86501650	20QKF70505250
19QFV19001050	19QFA22004200	19QFA90506000	19QGA00003750	19QGV86501800	20QKF70505400
19QFV20501050	19QFA23504200	19QFA10006000	19QGA00003900	19QGV86501950	20QKF70505550
19QFV23501050	19QFA25004200	19QFA11506000	19QGA00004050	19QGV86502100	20QKF70505700
19QFV25001050	19QFA26504200	19QFA13006000	19QGA00004200	19QGV86502250	20QKF70505850
19QFV26501050	19QFA28004200	19QFA14506000	19QGA00004350	19QGV86502400	20QKF70506000
19QFV28001050	19QGA29504200	19QFA16006000	19QGA00004500	19QGV86502550	20QKF70506150
19QGV29501050	19QGA31004200	19QFA17506000	19QGA00004650	19QGV88000450	20QKF72003450
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19QGV41501050	19QGA35504200	19QFA22006000	19QGA01503000	19QGV88001650	20QKF72003900
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19QGV44501050	19QGA38504200	19QFA25006000	19QGA01503300	19QGV88001950	20QKF72004200
19QGV46001050	19QGA40004200	19QFA26506000	19QGA01503450	19QGV88002100	20QKF72004350
19QGV47501050	19QGA41504200	19QFA28006000	19QGA01503600	19QGV88002250	20QKF72004500
19QGV49001050	19QGA43004200	19QGA29506000	19QGA01503750	19QGV88002400	20QKF72004650
19QGV50501050	19QGA44504200	19QGA31006000	19QGA01503900	19QGV88002550	20QKF72004800
19QGV52001050	19QGA46004200	19QGA32506000	19QGA01504050	19QGV89500450	20QKF72004950
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19QGV55001050	19QGA49004200	19QGA35506000	19QGA01504350	19QGV89500750	20QKF72005250
19QGV56501050	19QGA50504200	19QGA37006000	19QGA01504500	19QGV89501500	20QKF72005400
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19QFV22001200	19QGA59504200	19QGA46006000	19QGA03003300	19QGV89502400	20QKF73503450
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19QGV32501200	19QGA70004200	19QGA56506000	19QGA03004350	19QGV91001950	20QKF73504500
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19QGV47501200	19QFA22004350	19QGA70006000	19QGA04503600	19QGV92501800	20QKF73505850
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19QGV65501350	19QFA25004500	19QHA36006000	19QGA09003900	19QHA28503150	20QKF78004650
19QGV67001350	19QFA26504500	19QHA37506000	19QGA09004050	19QHA28503300	20QKF78004800
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19QFV16001500	19QGA35504500	20QJF46506000	19QGA10502850	19QHA28504200	20QKF78005700
19QFV17501500	19QGA37004500	20QJF48006000	19QGA10503000	19QHA28504350	20QKF78005850
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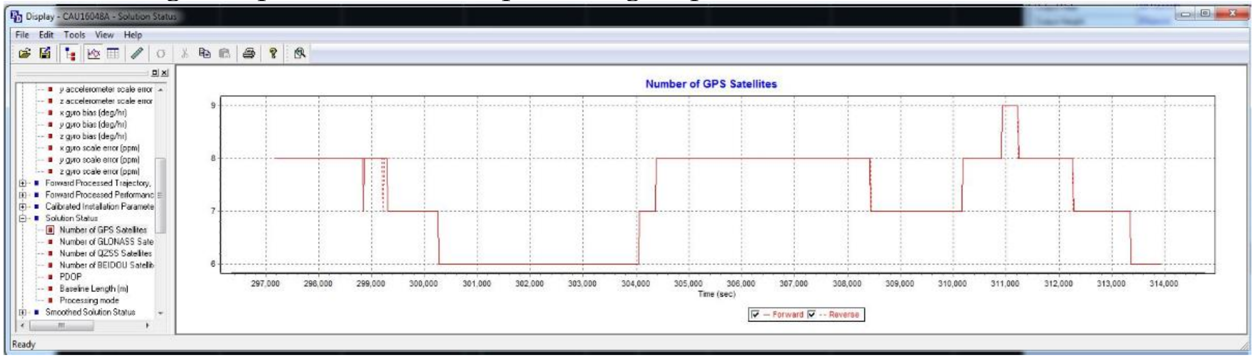
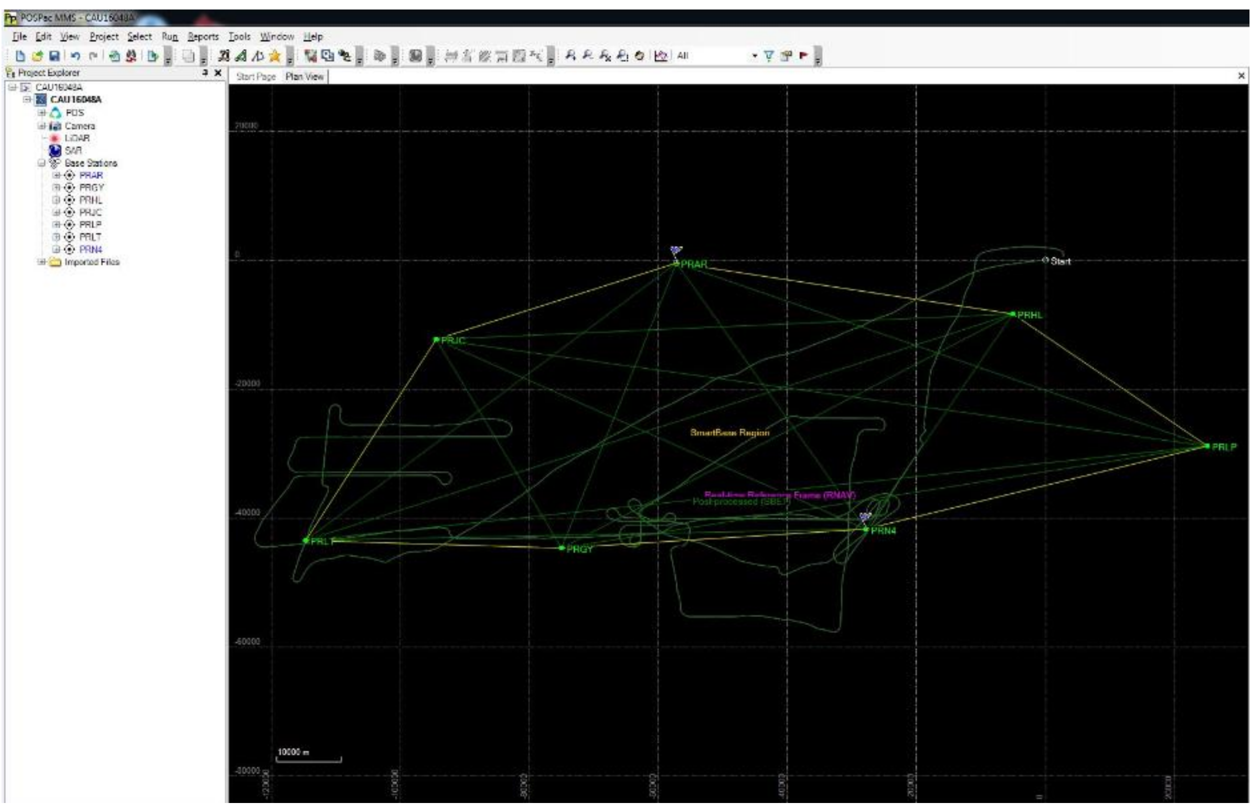
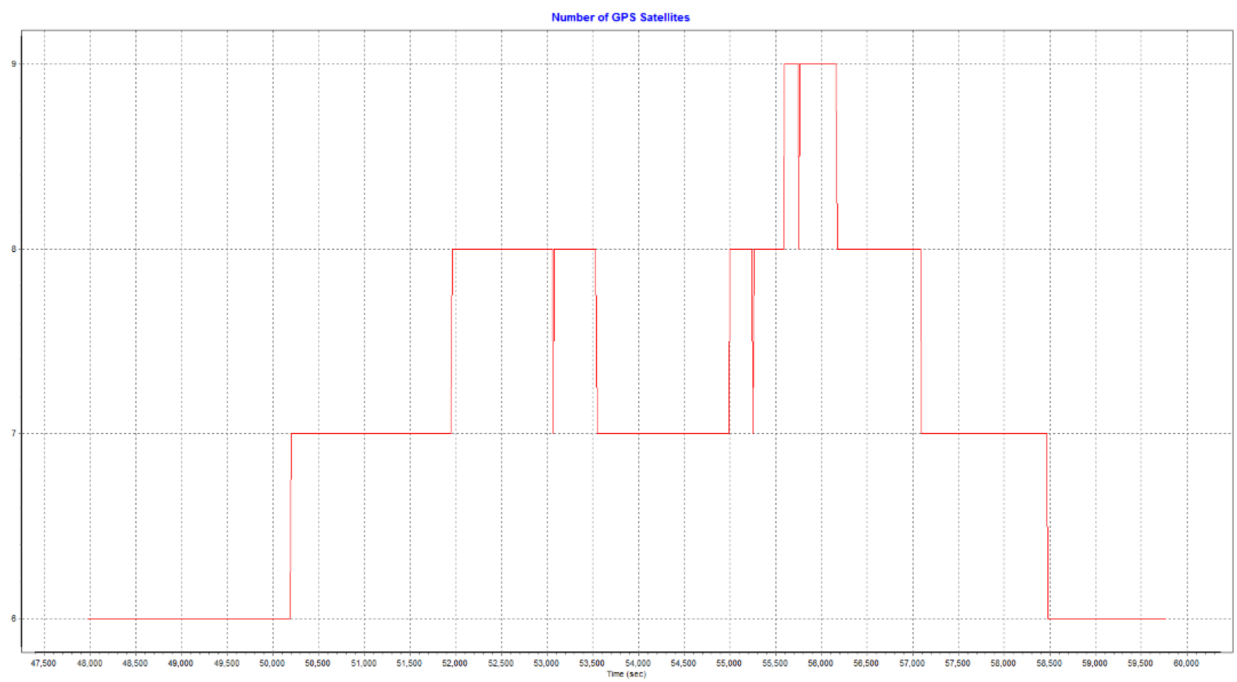
Appendix D: GPS Processing

The following examples show the GPS processing outputs.






Display - CAU16048A - SBET IAKAR Separation
File Edit Tools View Help
Time (sec)
North (m)
East (m)
Down (m)
DR mode
Ready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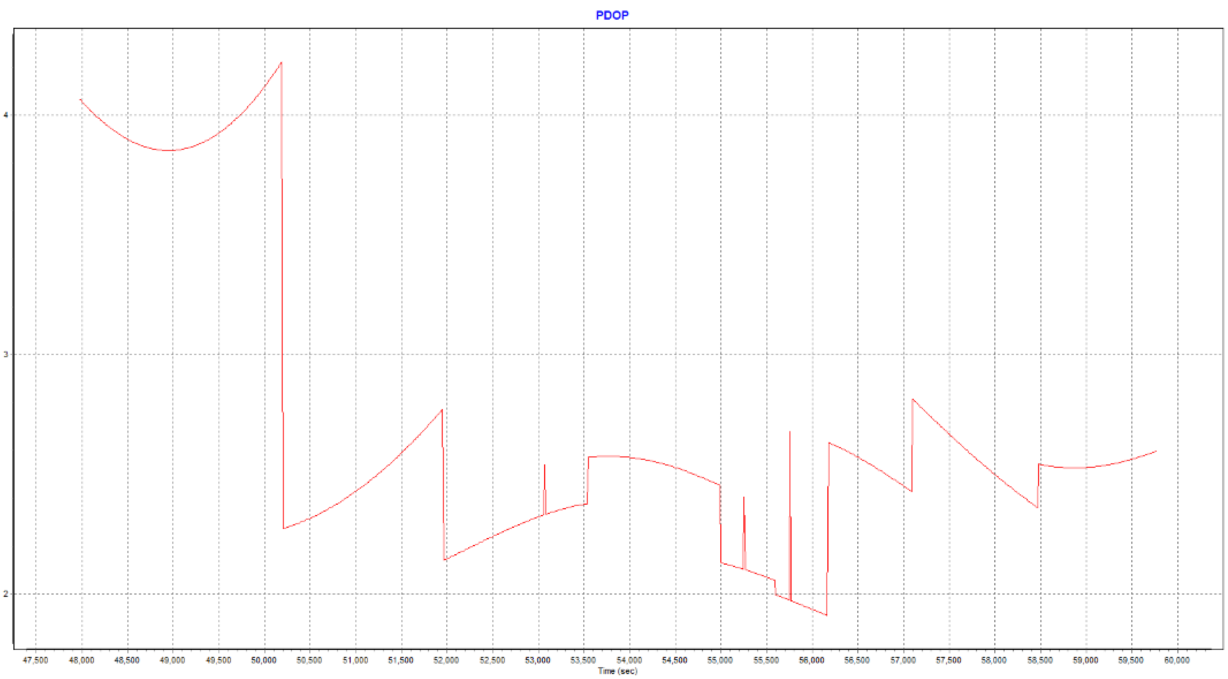
Time (sec)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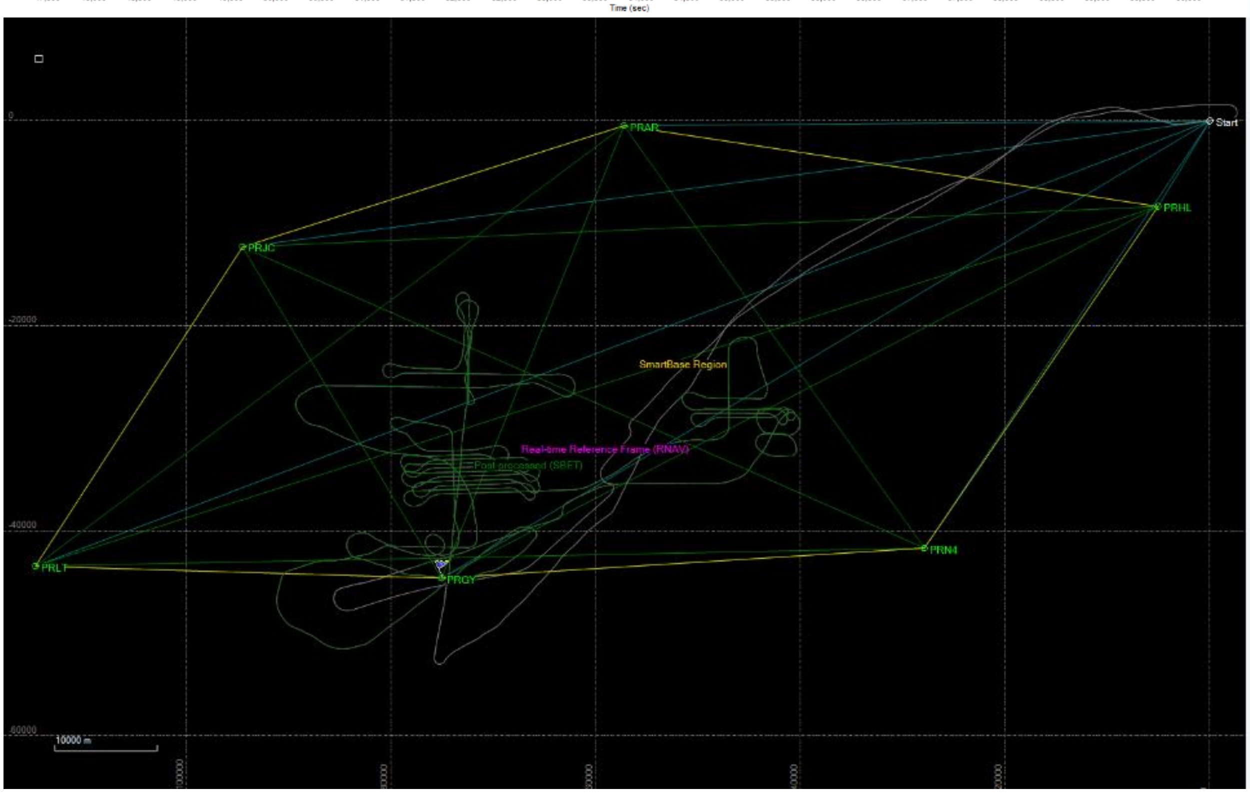
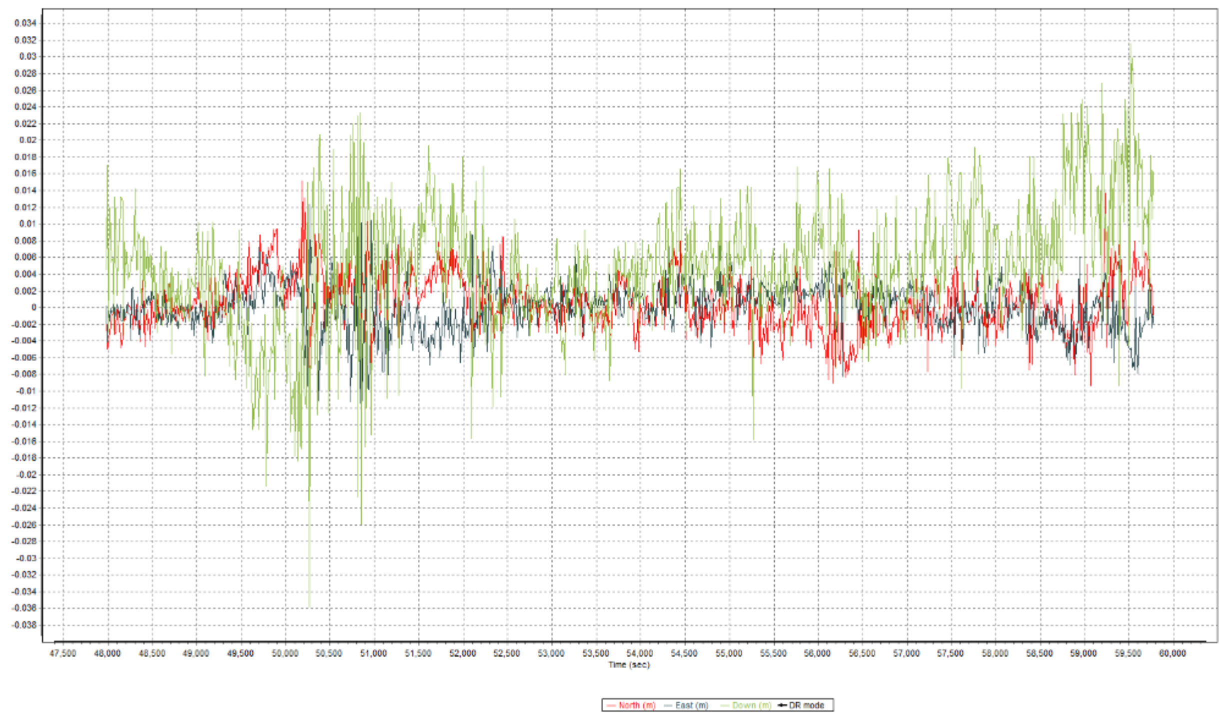
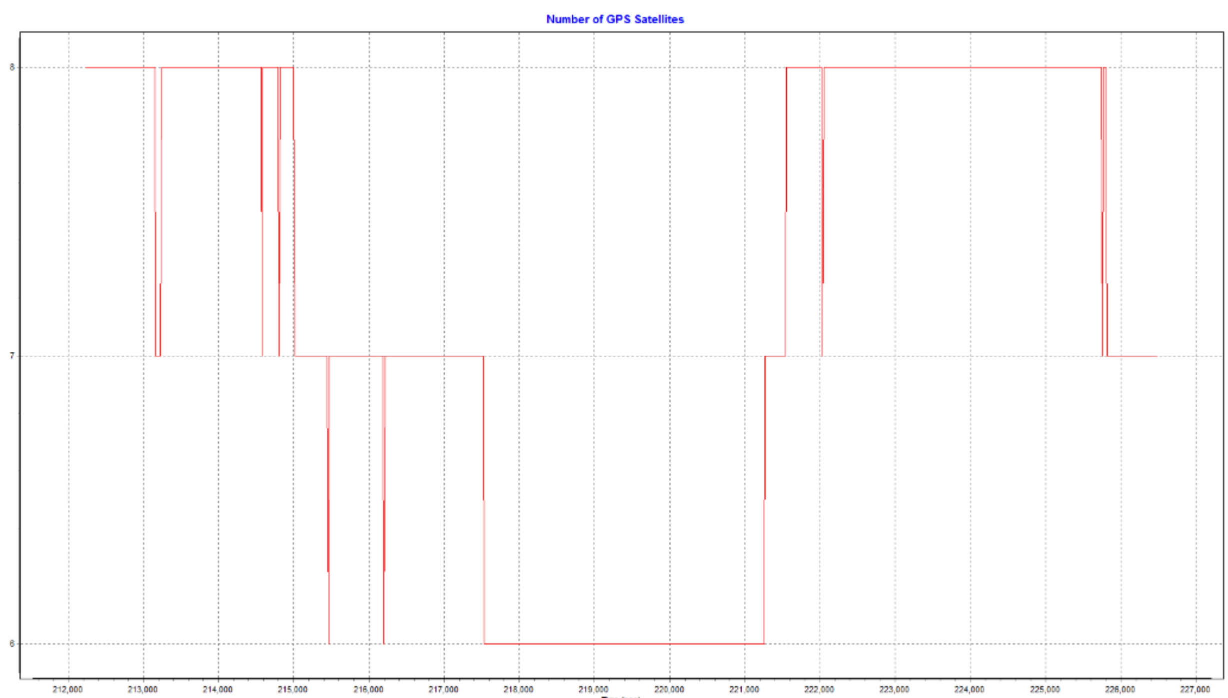
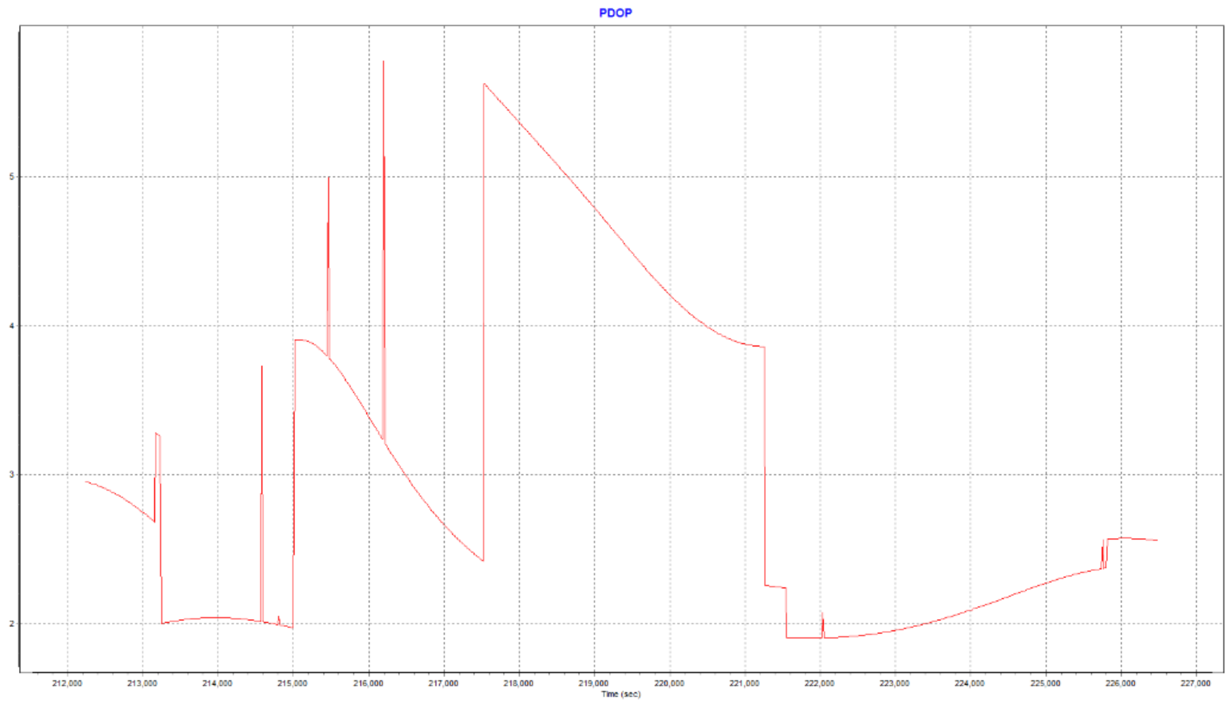
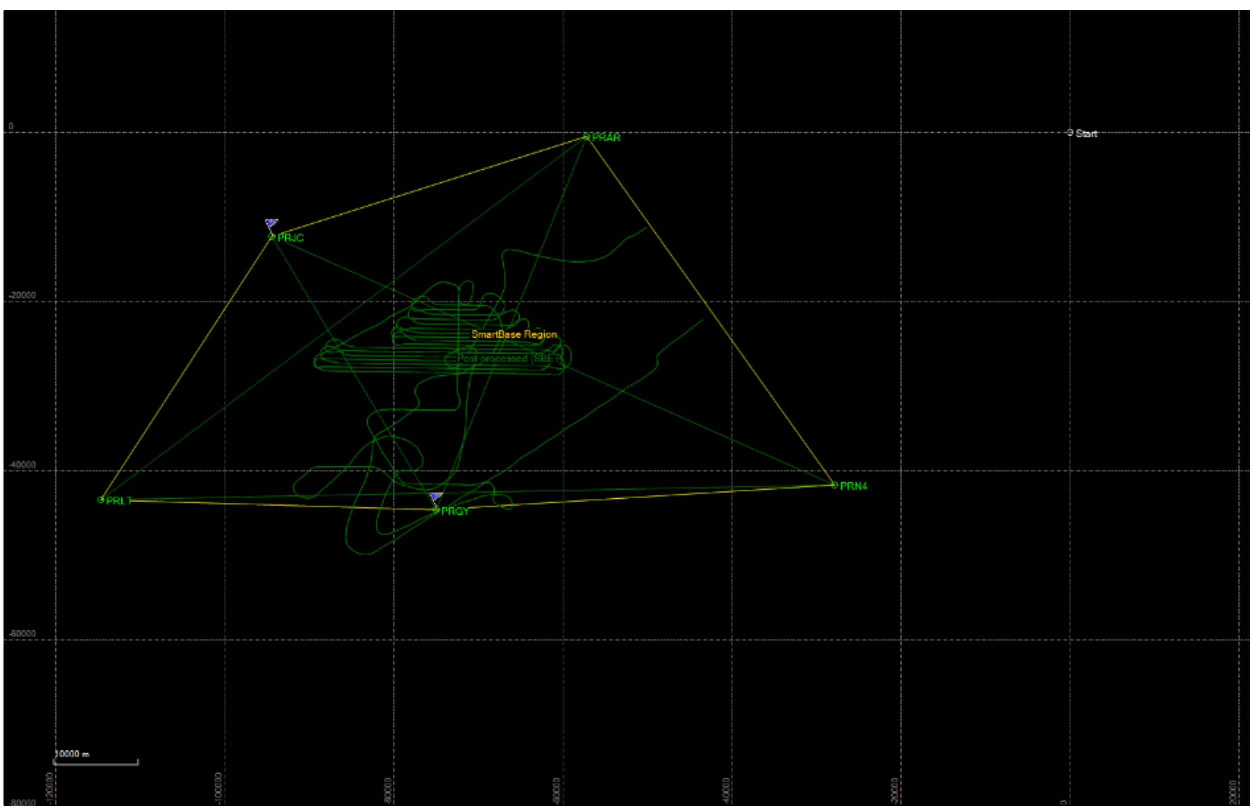
60,000
Time (sec)

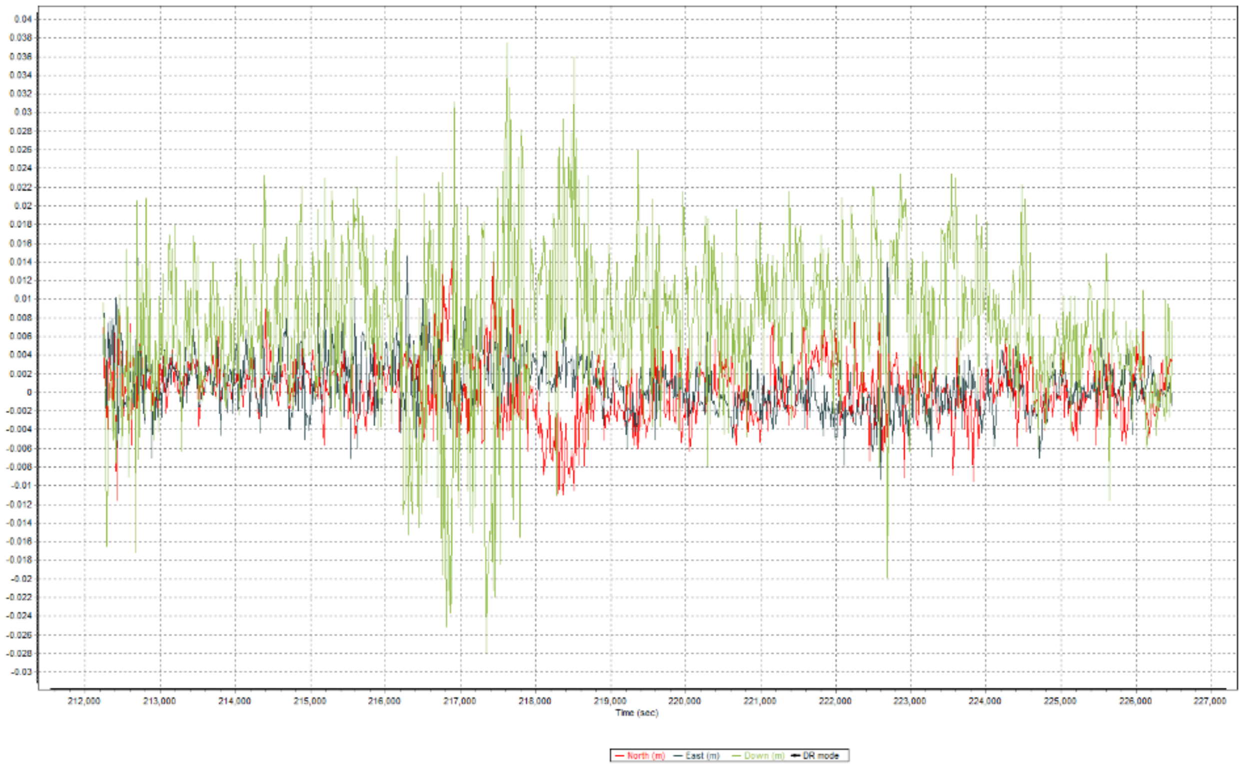

Start
PRAR
PRHL
PRJC
SmartBase Region
Real-time Reference Frame (RNAV)
Post-processed (SBET)
PRLT
PRQY
PRN4
10000 m


Time (sec)
North (m)
East (m)
Down (m)
DR mode


Number of GPS Satellites
Time (sec)


PDOP
5
4
3
2
212,000
213,000
214,000
215,000
216,000
217,000
218,000
219,000
220,000
221,000
222,000
223,000
224,000
225,000
226,000
227,000
Time (sec)


0
-20000
-40000
-60000
-80000
-120000
-100000
-80000
-60000
-40000
-20000
0
20000
PRAR
Start
PRJC
SmartBase Region
Post-processed (SBET)
PRN4
PRLT
PRQY
10000 m


0.04
0.038
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
-0.018
-0.02
-0.022
-0.024
-0.026
-0.028
-0.03
212,000
213,000
214,000
215,000
216,000
217,000
218,000
219,000
220,000
221,000
222,000
223,000
224,000
225,000
226,000
227,000
Time (sec)
North (m)
East (m)
Down (m)
DR mode


Number of GPS Satellites
8
7
6
304,000
304,200
304,400
304,600
304,800
305,000
305,200
305,400
305,600
305,800
306,000
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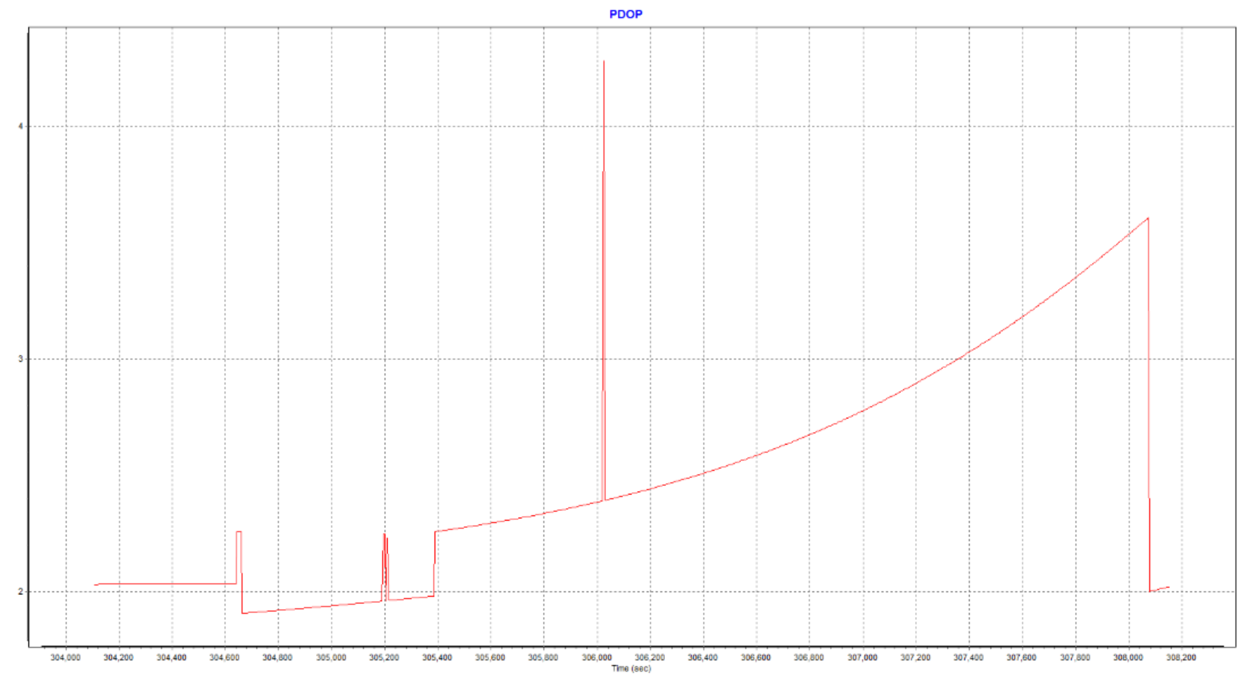
308,000
308,200
Time (sec)


PDOP
4
3
2
304,000
304,200
304,400
304,600
304,800
305,000
305,200
305,400
305,600
305,800
306,000
306,200
306,400
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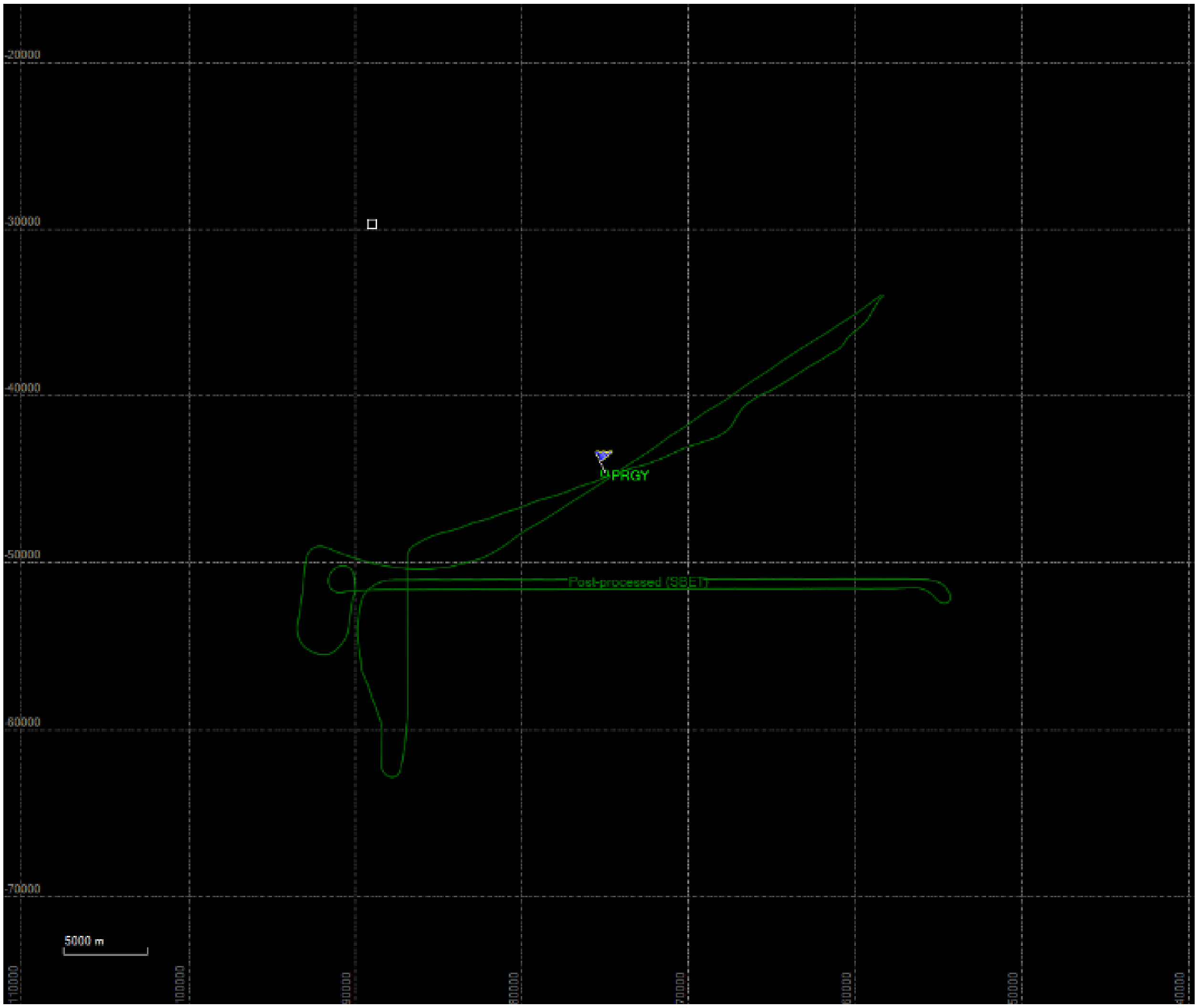
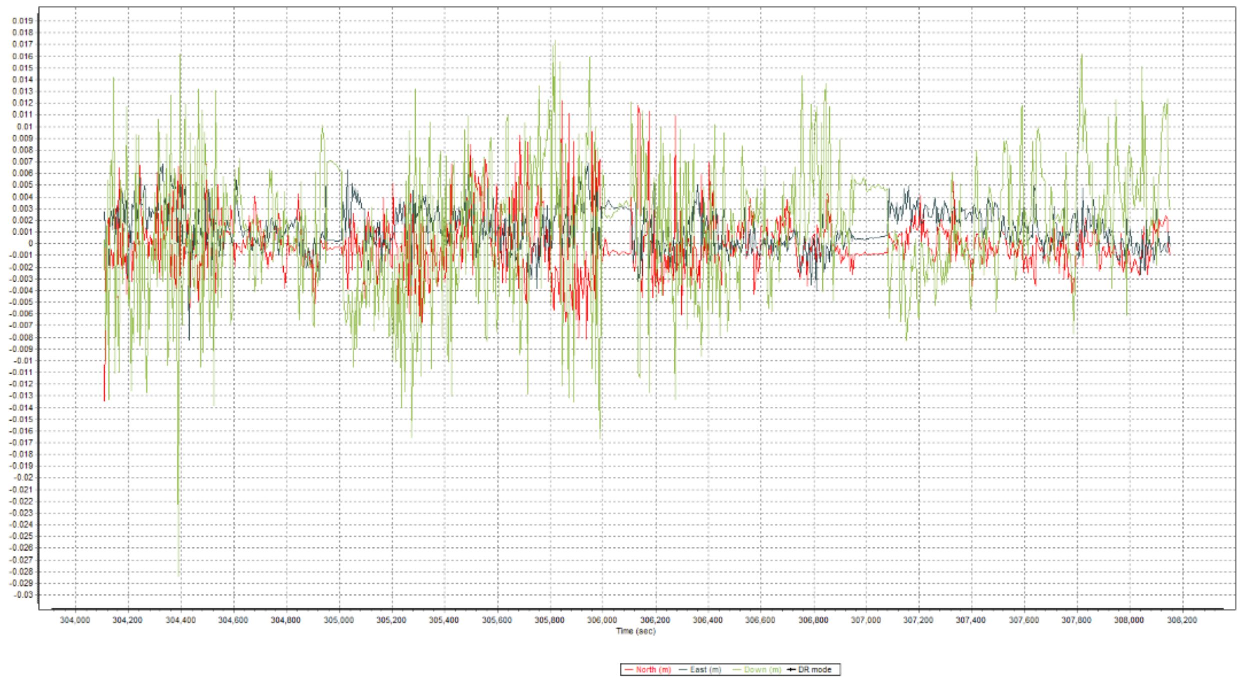
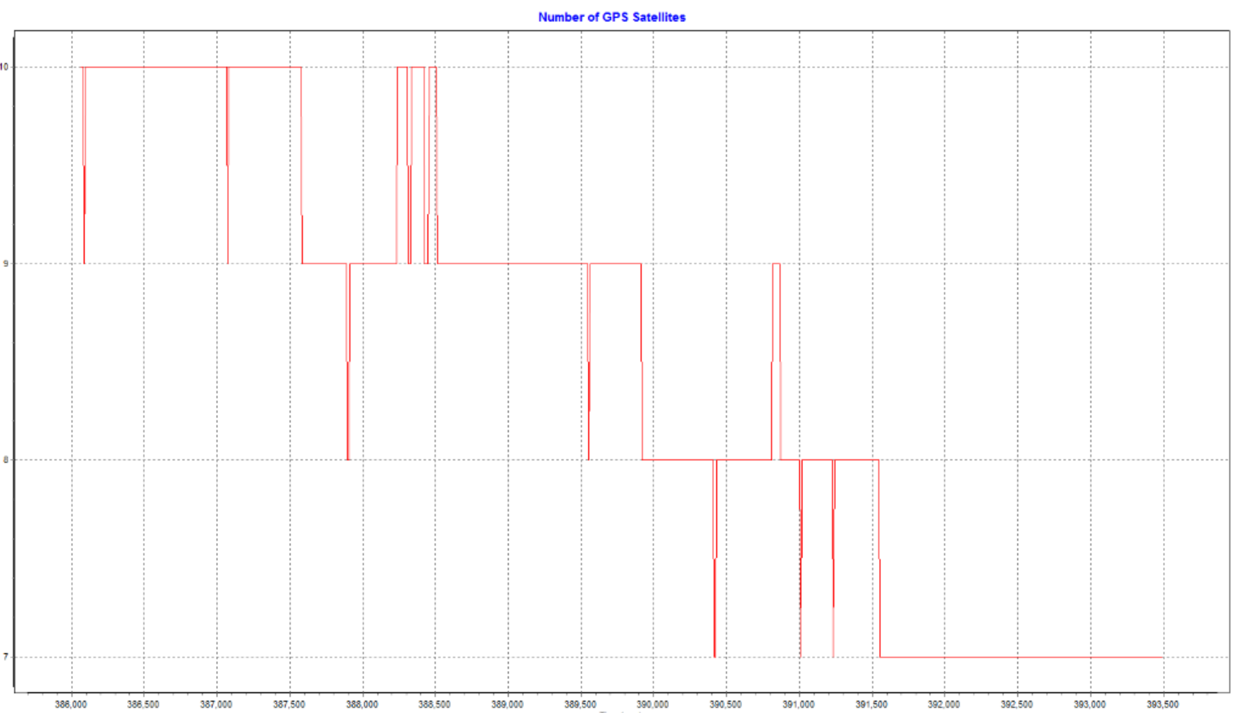
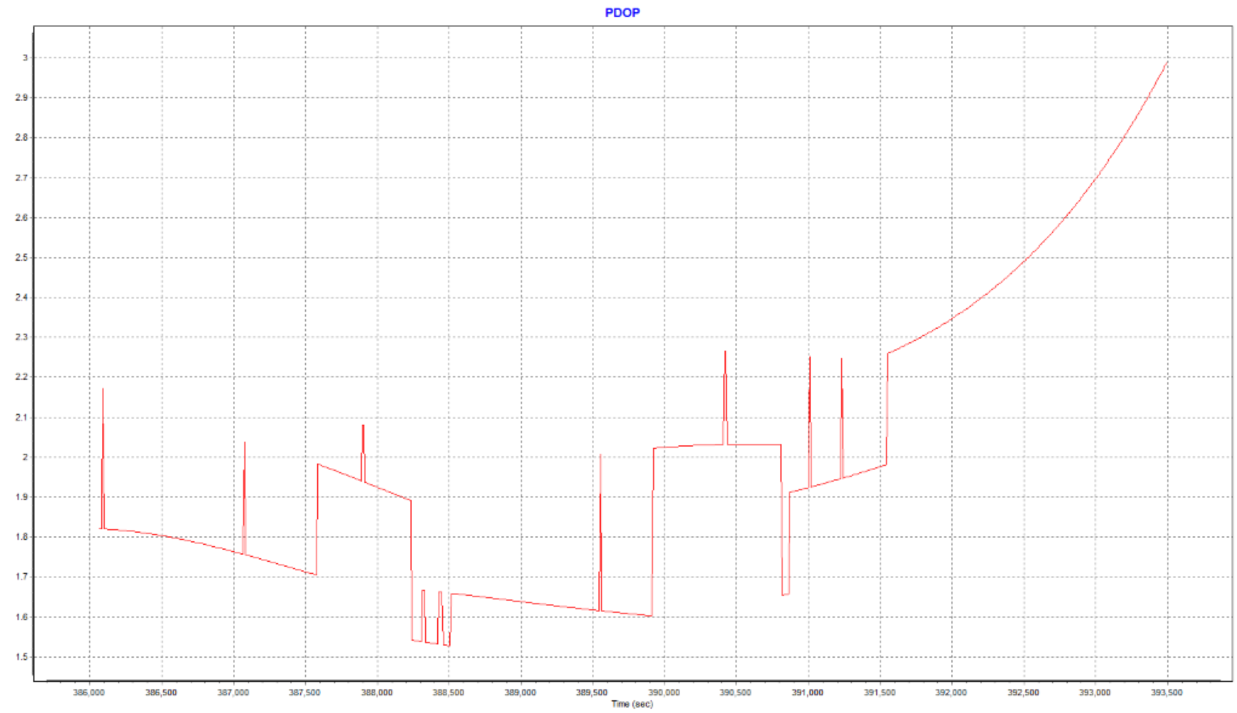
306,800
307,000
307,200
307,400
307,600
307,800
308,000
308,200
Time (sec)


-20000
-30000
-40000
-50000
-60000
-70000
PRGY
Post-processed (SBET)
5000 m


Time (sec)
North (m)
East (m)
Down (m)
DR mode


Number of GPS Satellites
Time (sec)


PDOP
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
386,000
386,500
387,000
387,500
388,000
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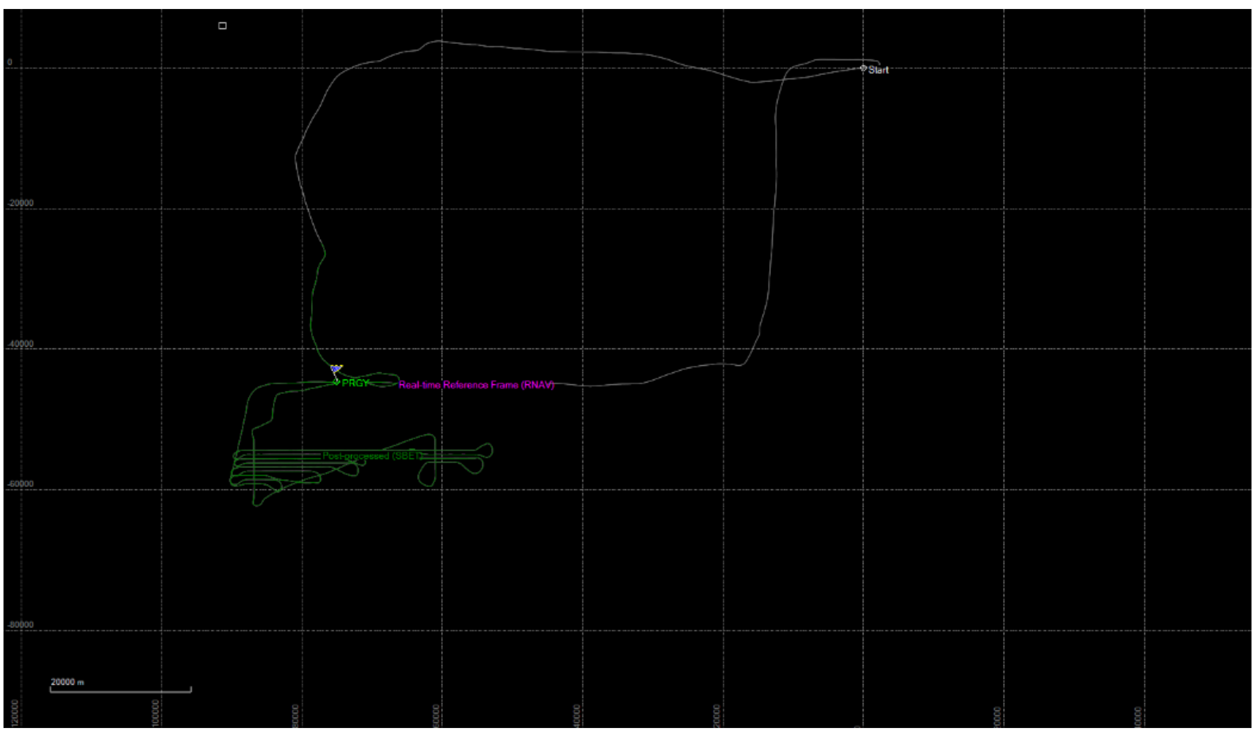
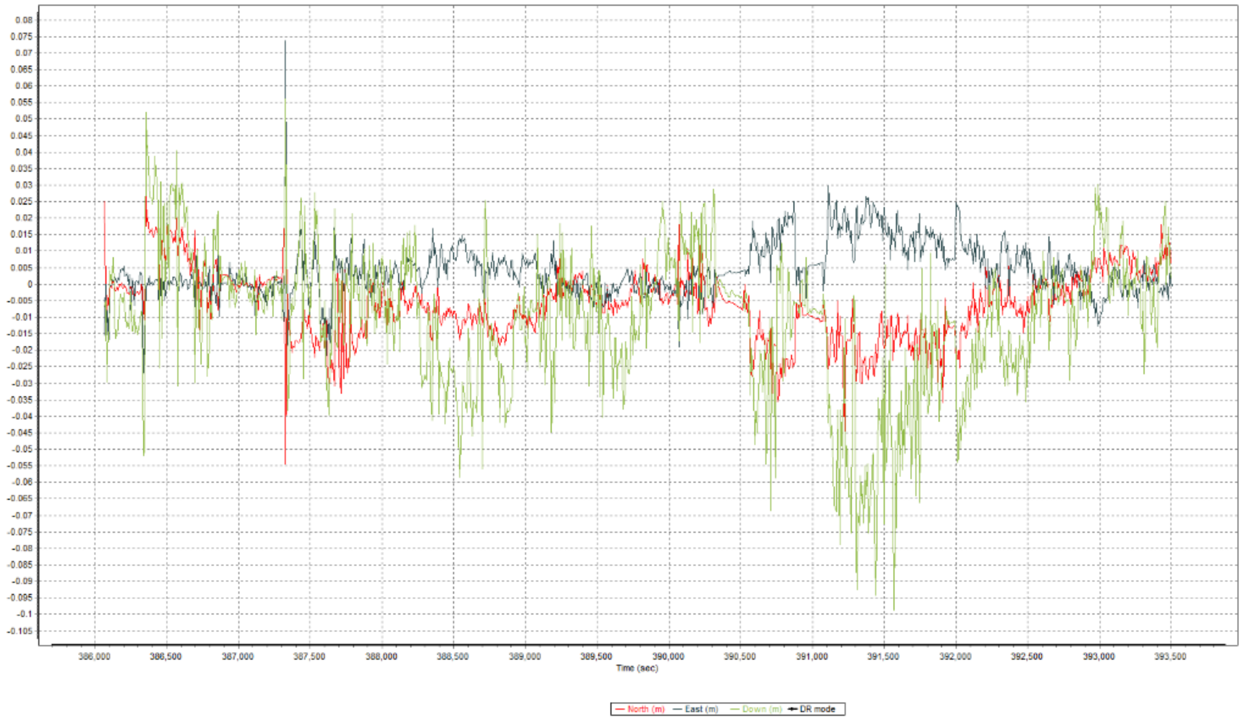
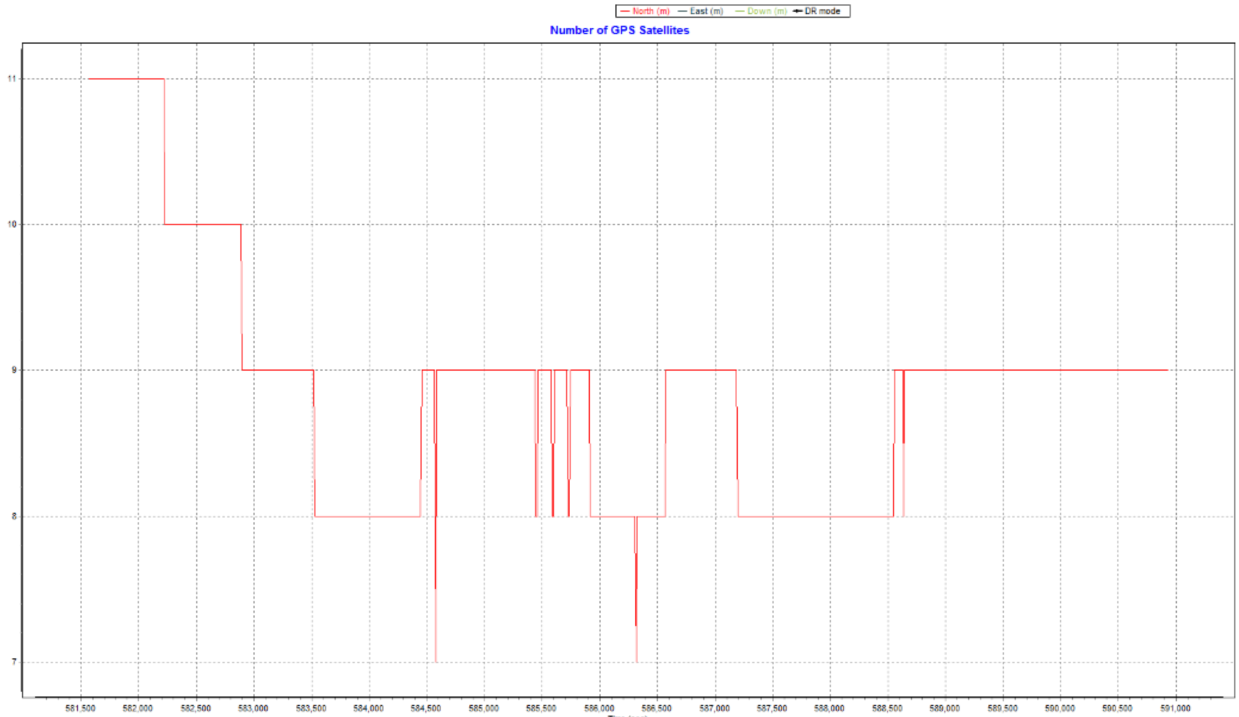
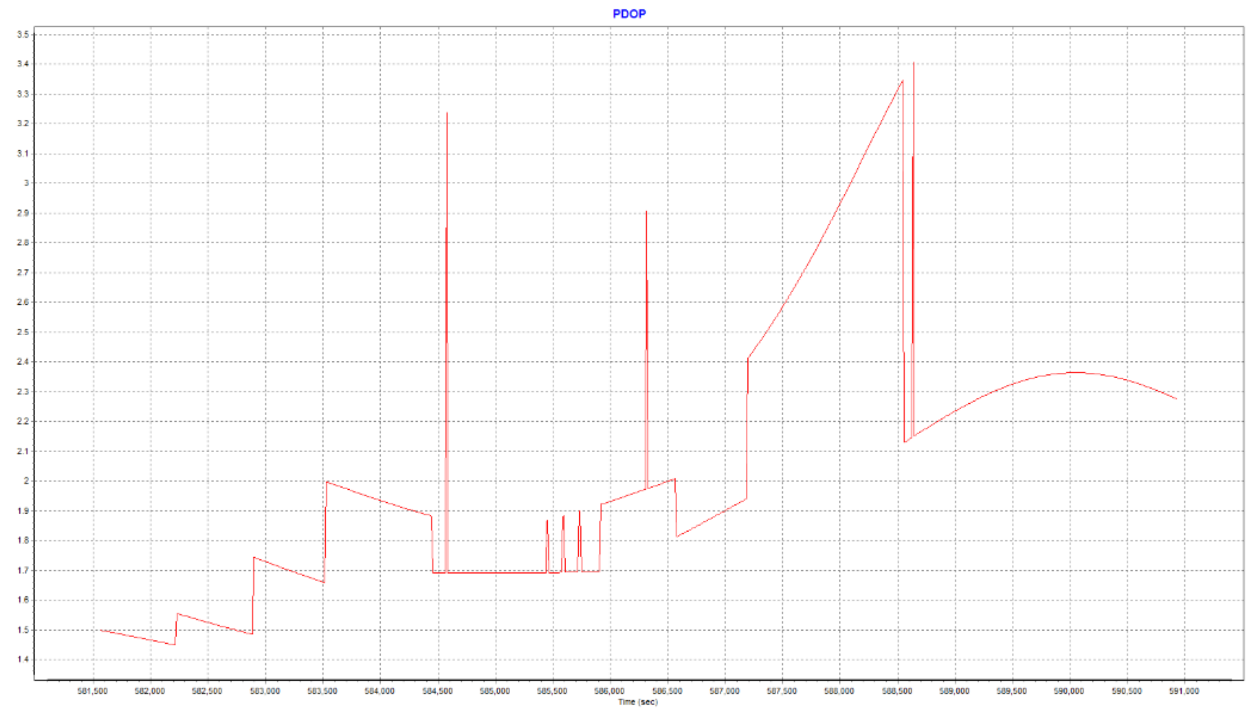
393,000
393,500
Time (sec)

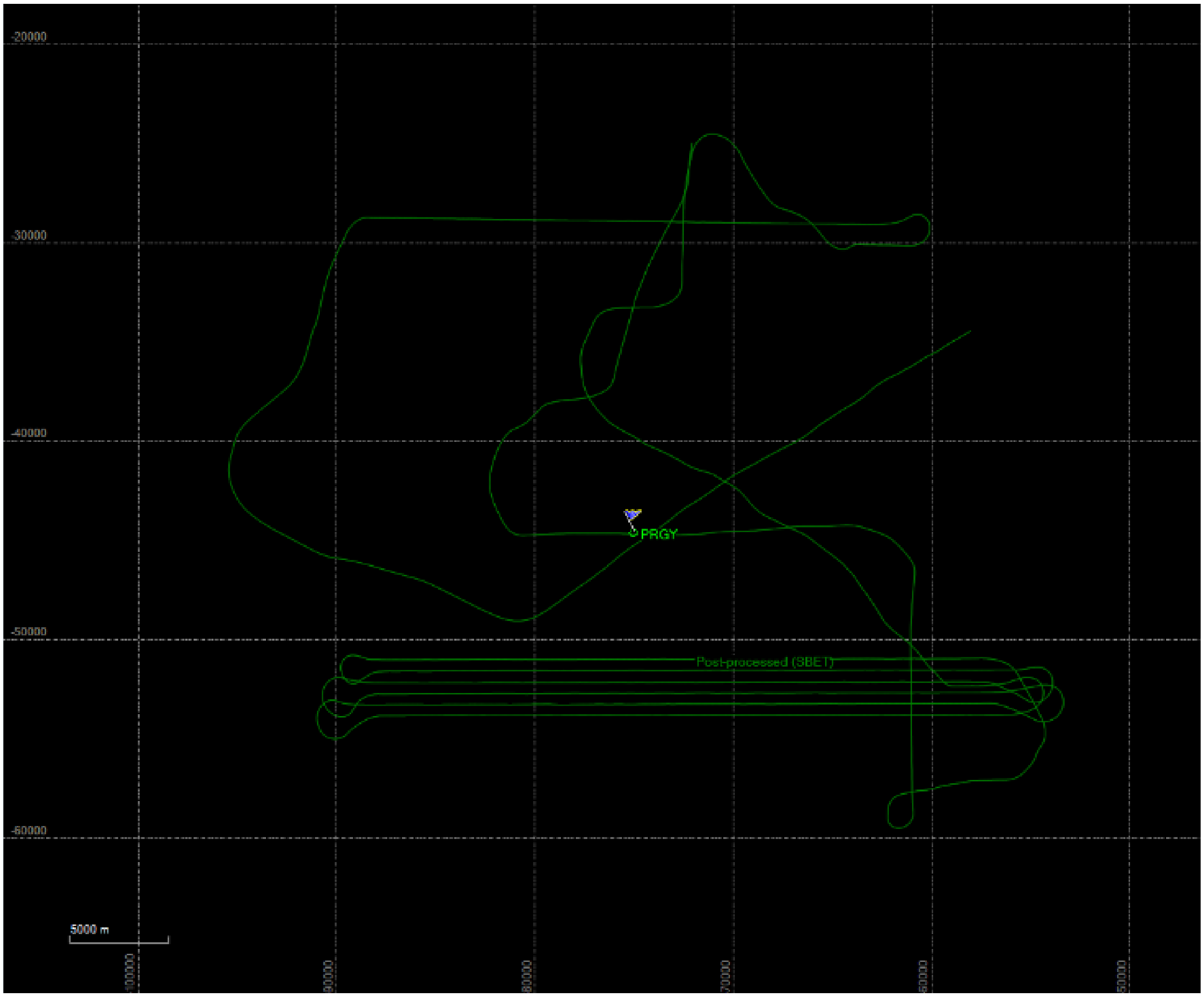

0
-20000
-40000
-60000
-80000
Start
PRGY
Real-time Reference Frame (RNAV)
Post-processed (SBET)
20000 m

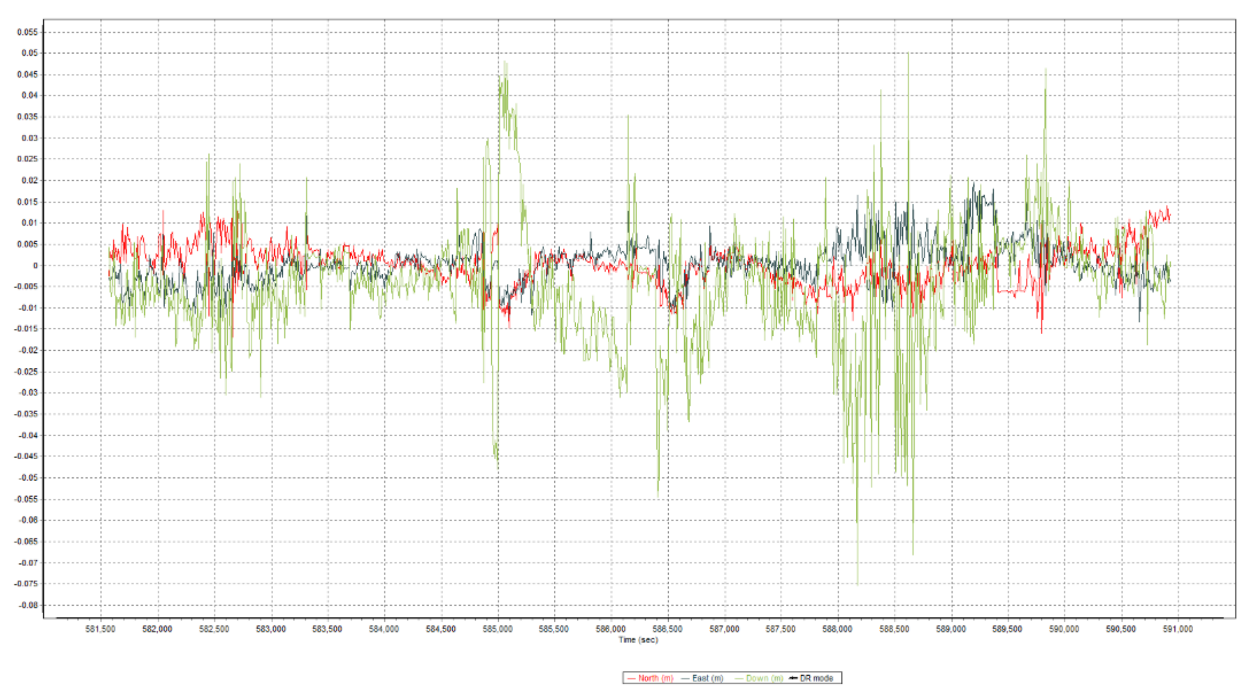
Dewberry®

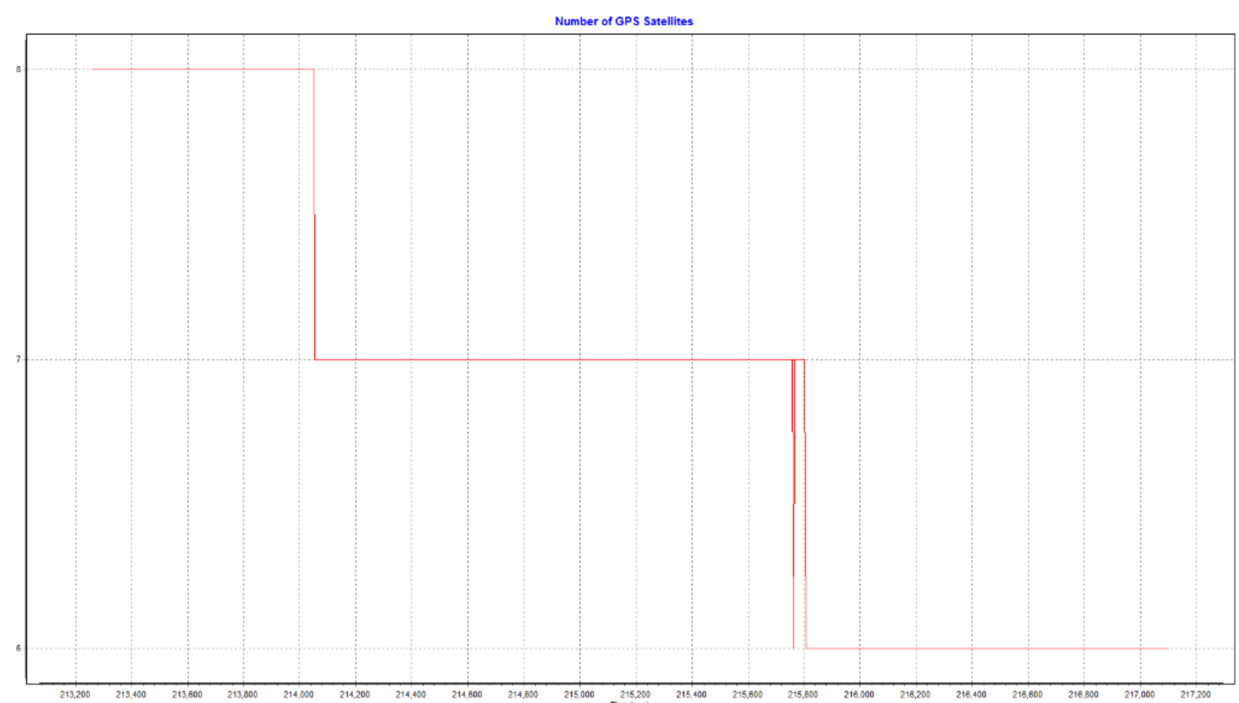

Time (sec)
North (m)
East (m)
Down (m)
DR mode

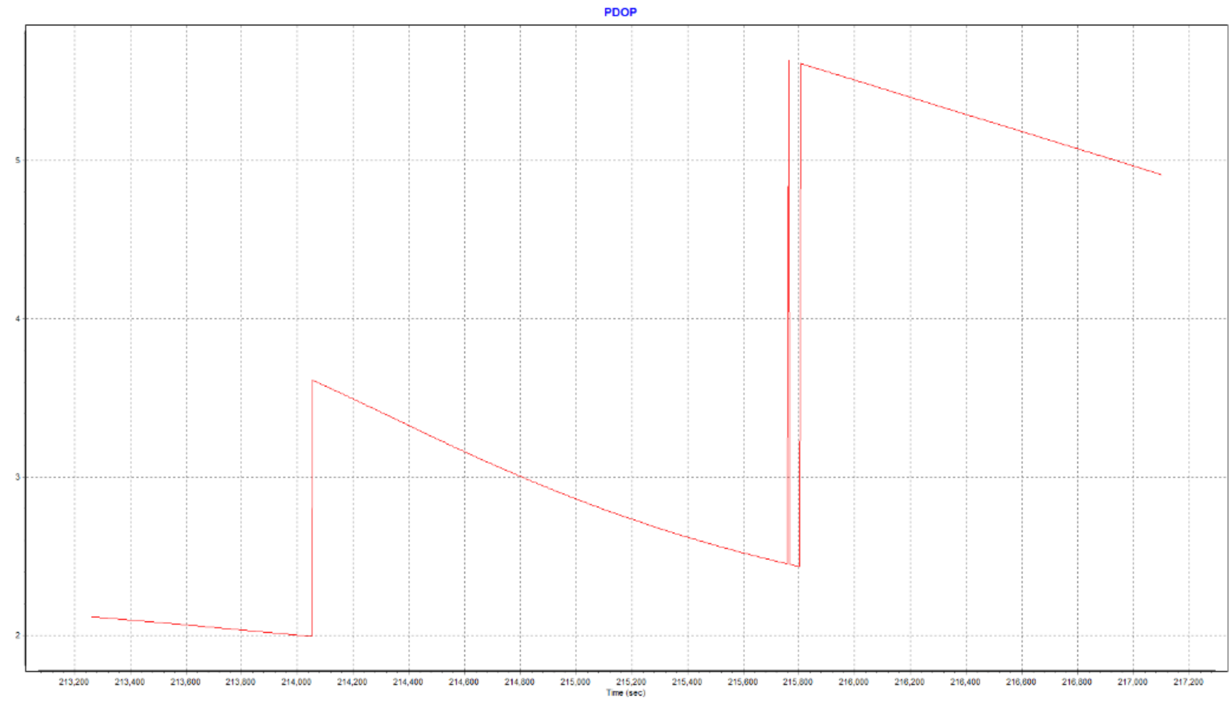

Number of GPS Satellites
Time (sec)

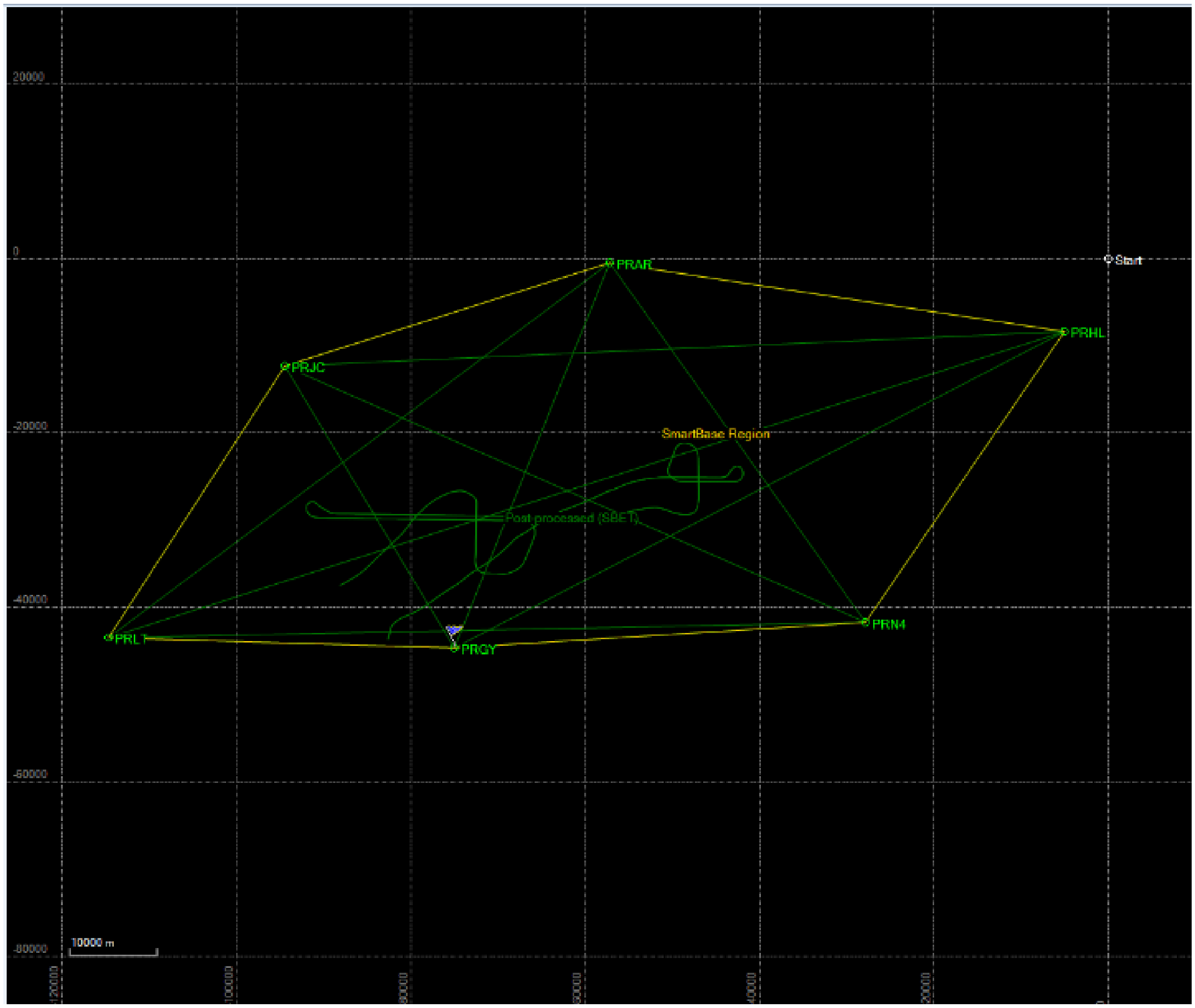

PDOP
Time (sec)

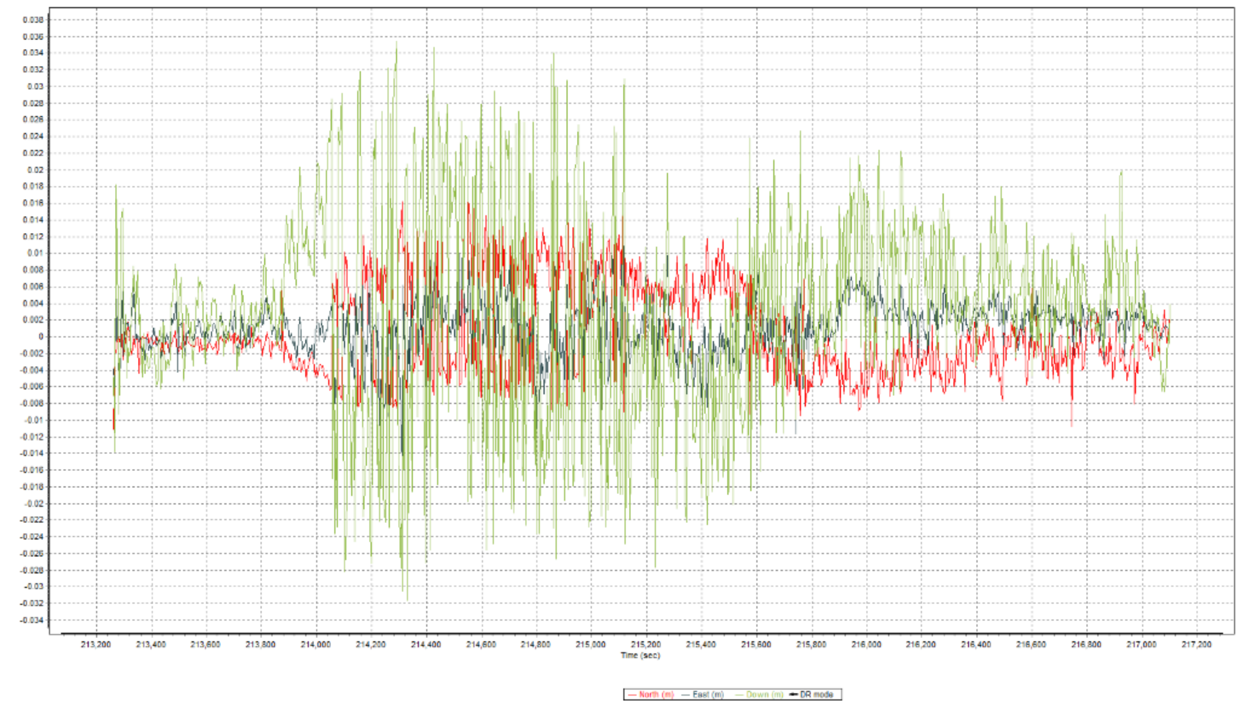

-20000
-30000
-40000
-50000
-60000
PRGY
Post-processed (SBET)
5000 m
100000
90000
80000
70000
60000
50000

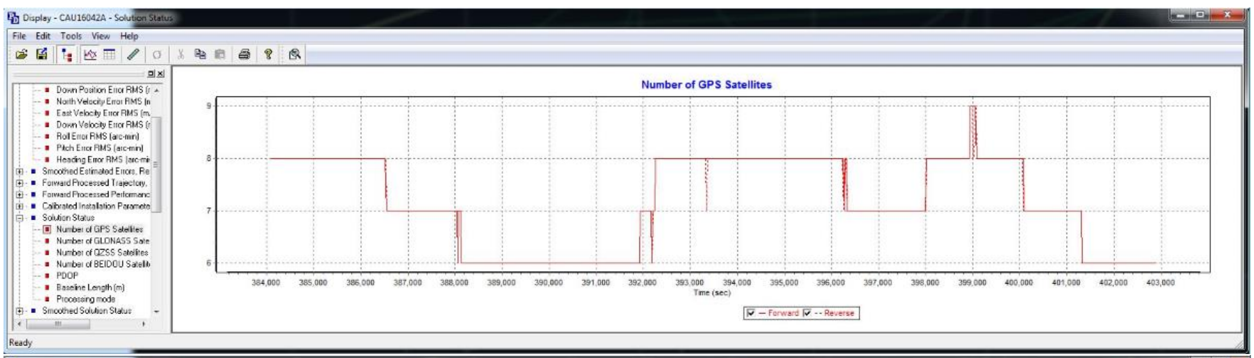

Time (sec)
North (m)
East (m)
Down (m)
DR mode

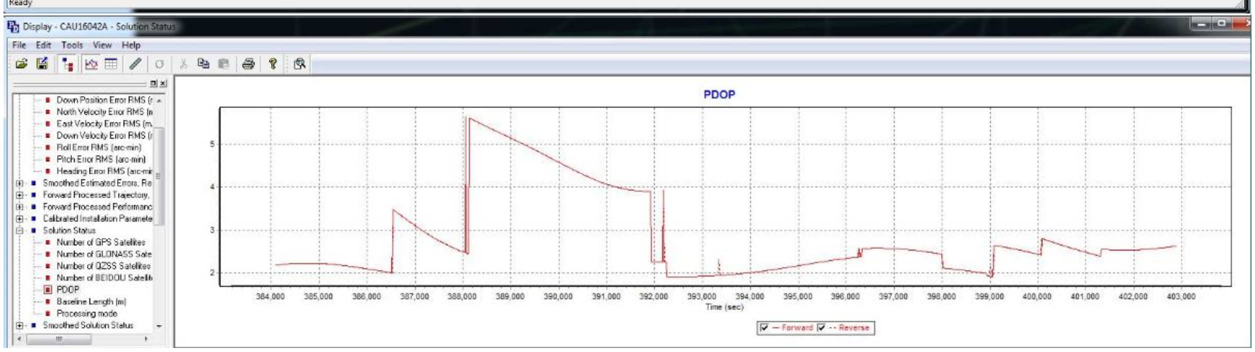

Number of GPS Satellites
Time (sec)

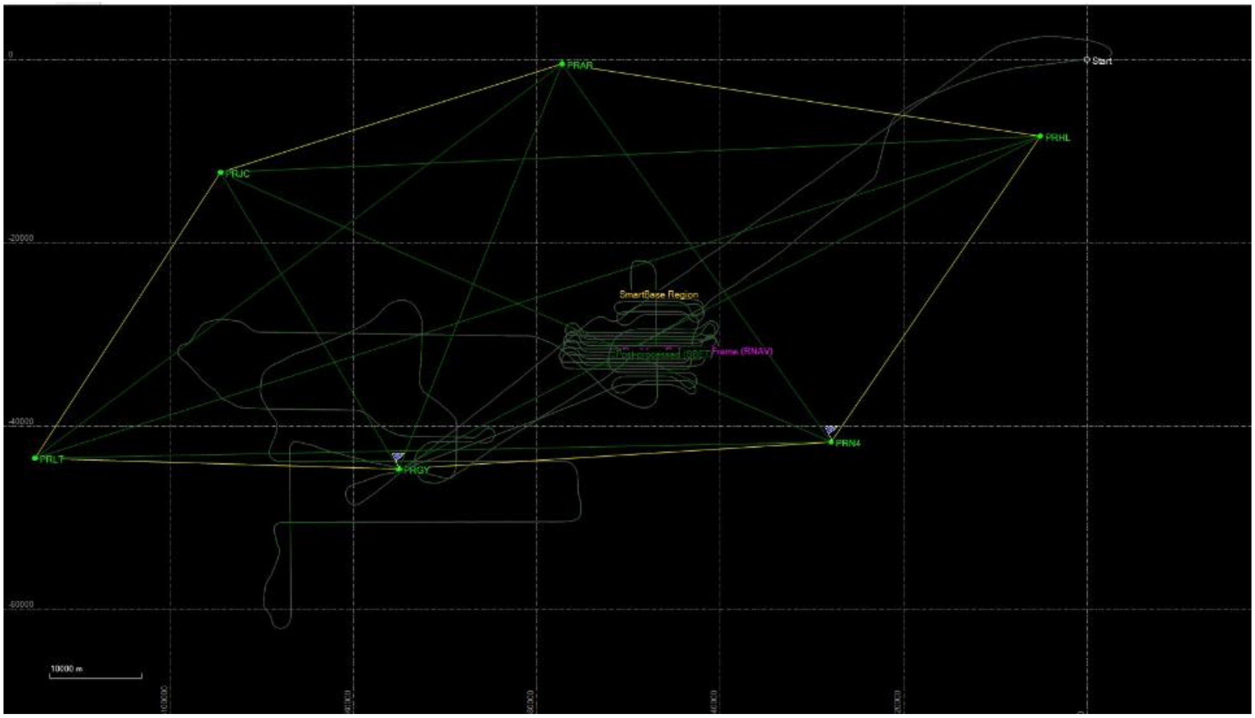

PDOP
5
4
3
2
213,200
213,400
213,600
213,800
214,000
214,200
214,400
214,600
214,800
215,000
215,200
215,400
215,600
215,800
216,000
216,200
216,400
216,600
216,800
217,000
217,200
Time (sec)

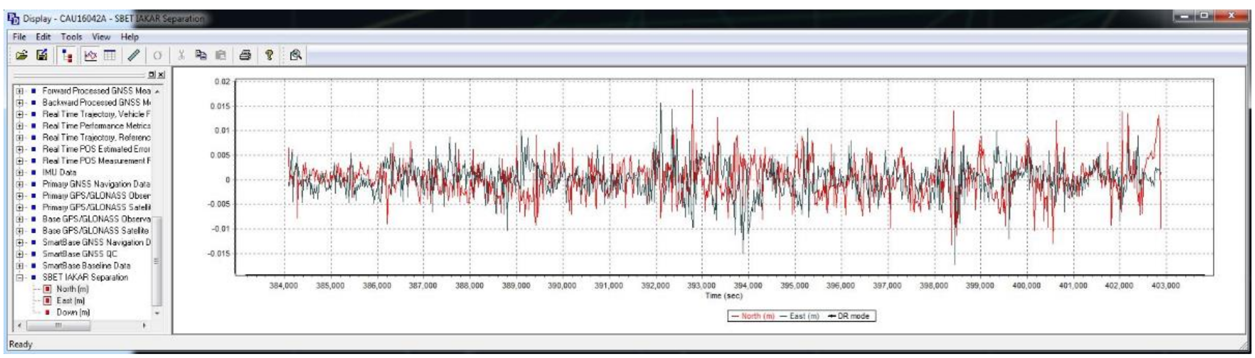

20000
0
-20000
-40000
-60000
-80000
PRAR
Start
PRHL
PRJC
SmartBase Region
Post-processed (SBET)
PRN4
PRLT
PRGY
10000 m
120000
100000
80000
60000
40000
20000
0

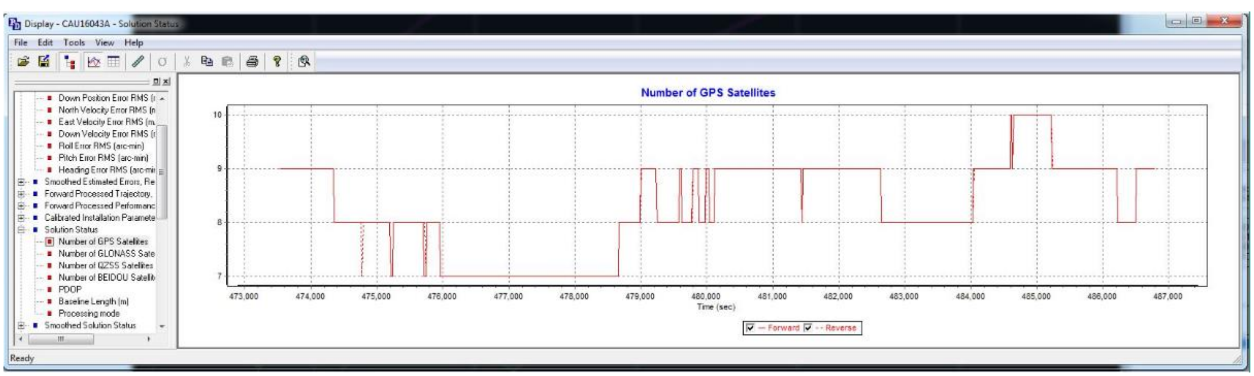

Time (sec)
North (m)
East (m)
Down (m)
DR mode

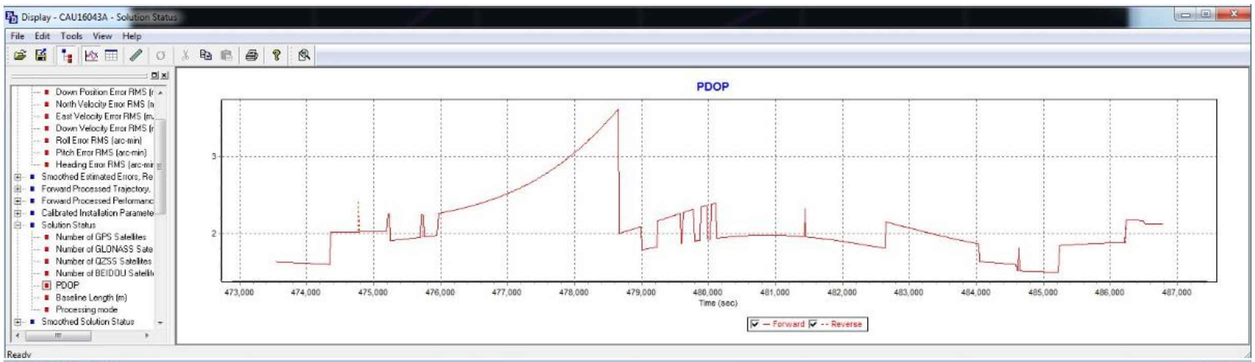

Display - CAU16042A - Solution Status
File Edit Tools View Help
Number of GPS Satellites
Time (sec)
Forward
Reverse
Ready

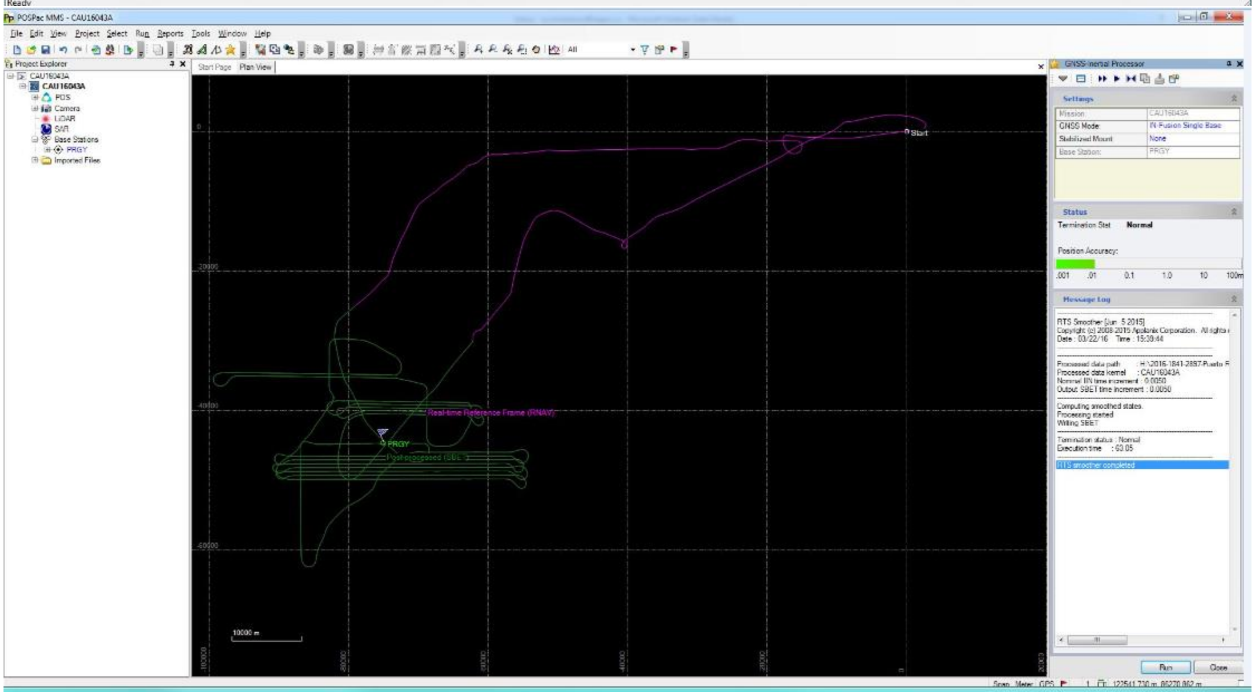

Display - CAU16042A - Solution Status
File Edit Tools View Help
PDOP
Time (sec)
Forward
Reverse


PRAR
PRHL
PRJC
SmartBase Region
PRN4
PRLT
PRGY
Start
10000 m

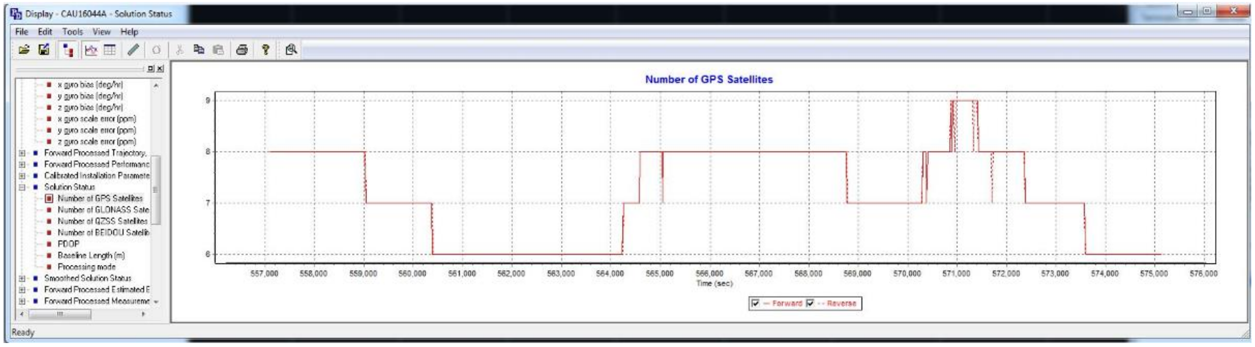

Display - CAU16042A - SBET IAKAR Separation
File Edit Tools View Help
SBET IAKAR Separation
North (m)
East (m)
Down (m)
Time (sec)
North (m)
East (m)
DR mode
Ready


Display - CAU16043A - Solution Status
File Edit Tools View Help
Number of GPS Satellites
Time (sec)
Forward
Reverse
Ready

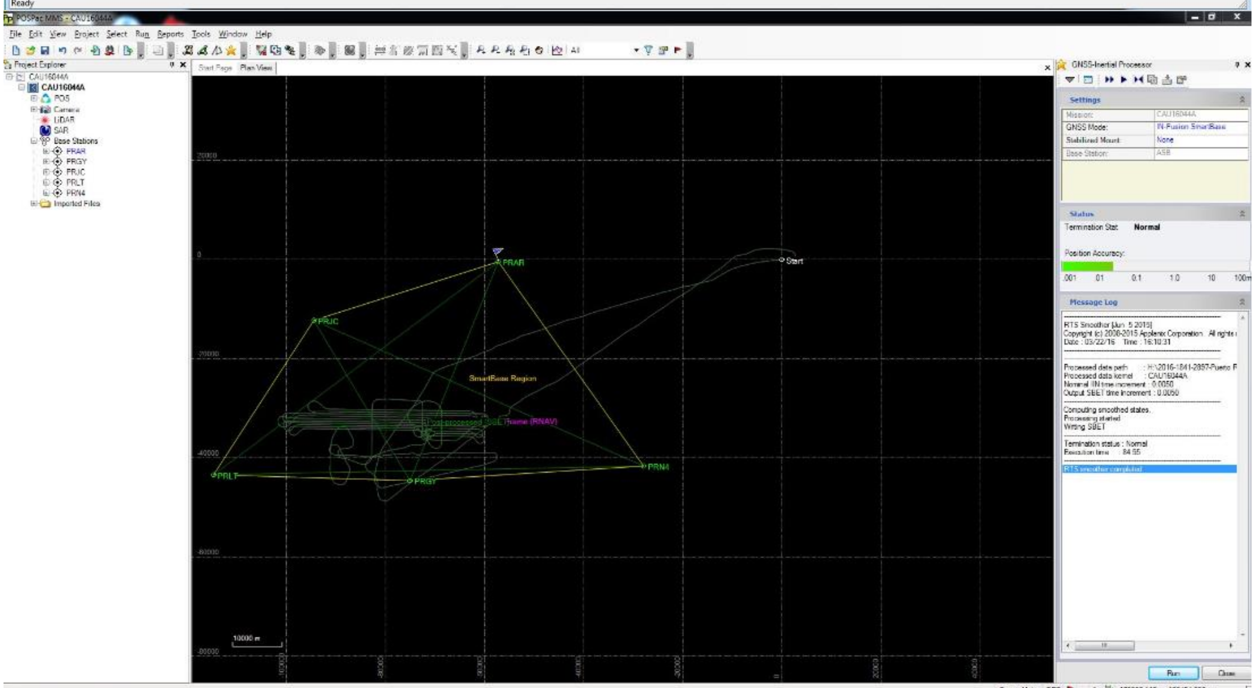

Display - CAU16043A - Solution Status
PDOP
Time (sec)
Forward
Reverse


POSPac MMS - CAU16043A
Project Explorer
GNSS-Inertial Processor
Settings
Status
Message Log
Start
PRGY
RTS smoother completed
Run
Close

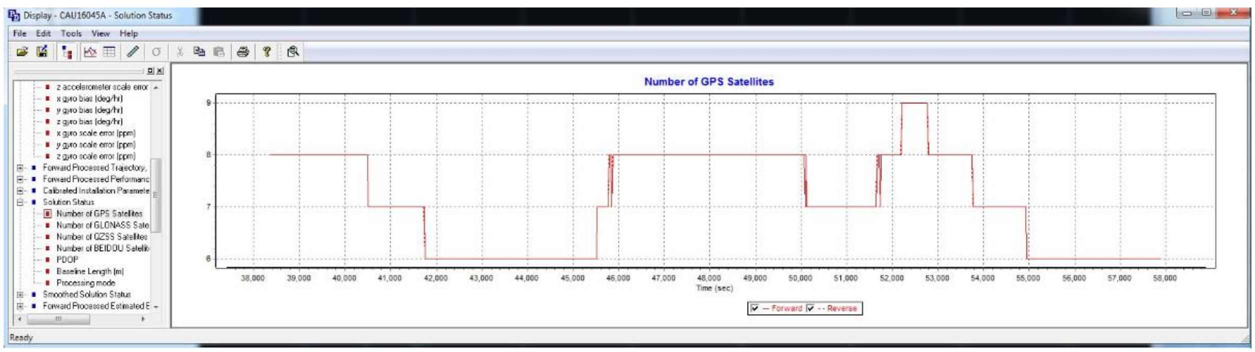

Display - CAU16043A - SBET IAKAR Separation
Time (sec)
North (m)
East (m)
Down (m)
DR mode

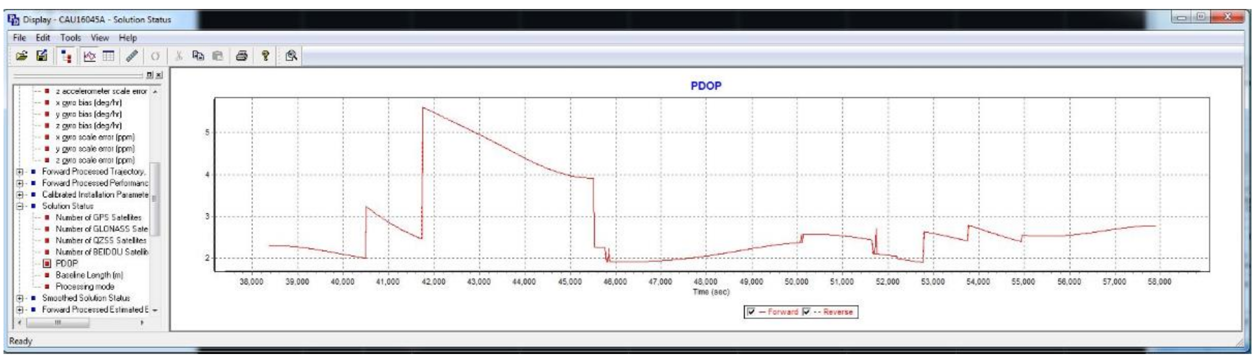

Display - CAU16044A - Solution Status
Number of GPS Satellites
Time (sec)
Forward
Reverse

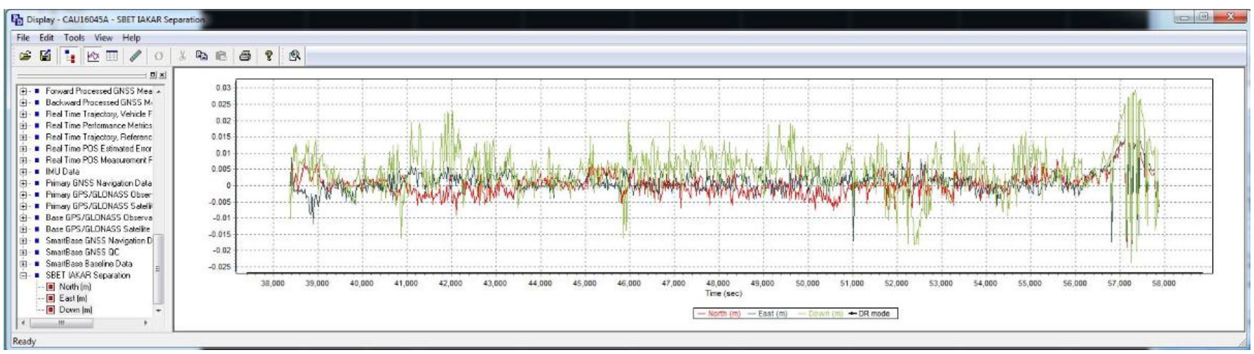

Display - CAU16044A - Solution Status
PDOP
Time (sec)
Forward
Reverse

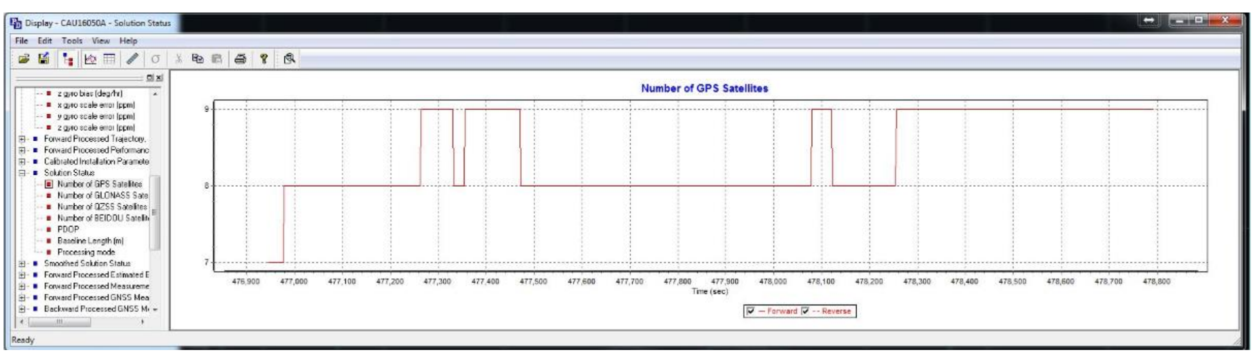

GNSS-Inertial Processor
Settings
Status
Message Log
SmartBase Region
PRAR
PRUC
PRLT
PRGY
PRN4
Start


Display - CAU16044A - SBET IAKAR Separation
SBET IAKAR Separation
North (m)
East (m)
Down (m)
Time (sec)
DR mode

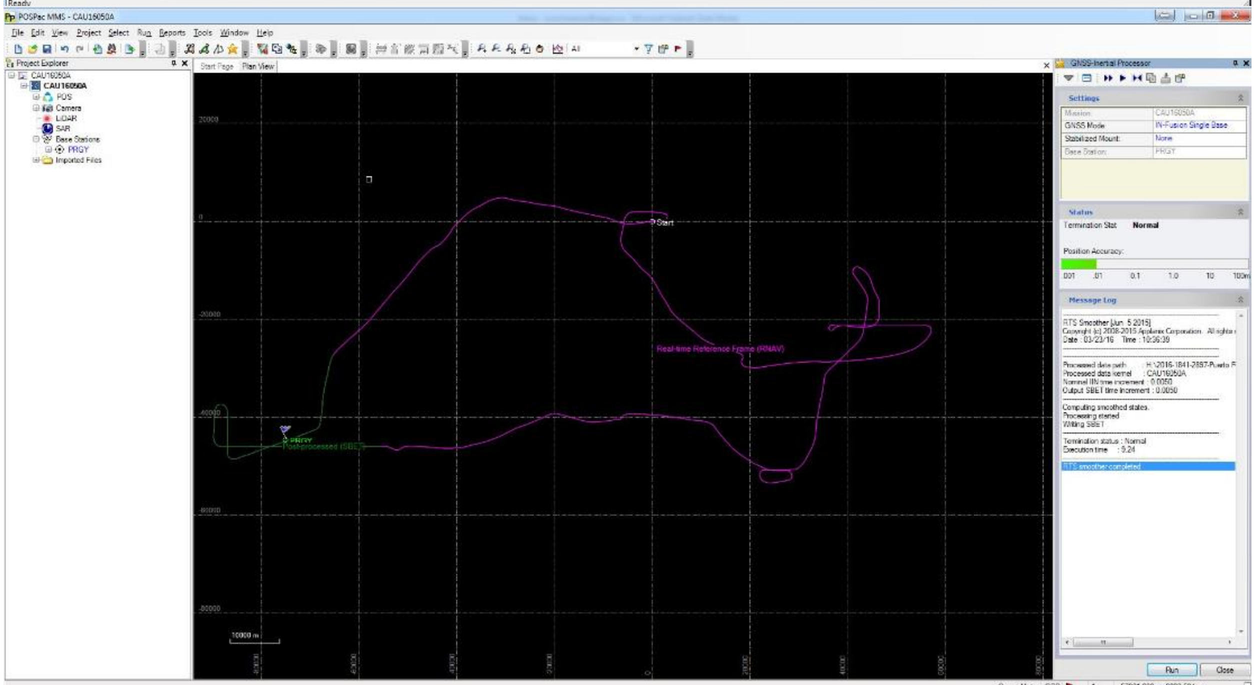

Display - CAU16045A - Solution Status
Number of GPS Satellites
Time (sec)
Forward
Reverse


Display - CAU16045A - Solution Status
PDOP
Time (sec)
Forward
Reverse

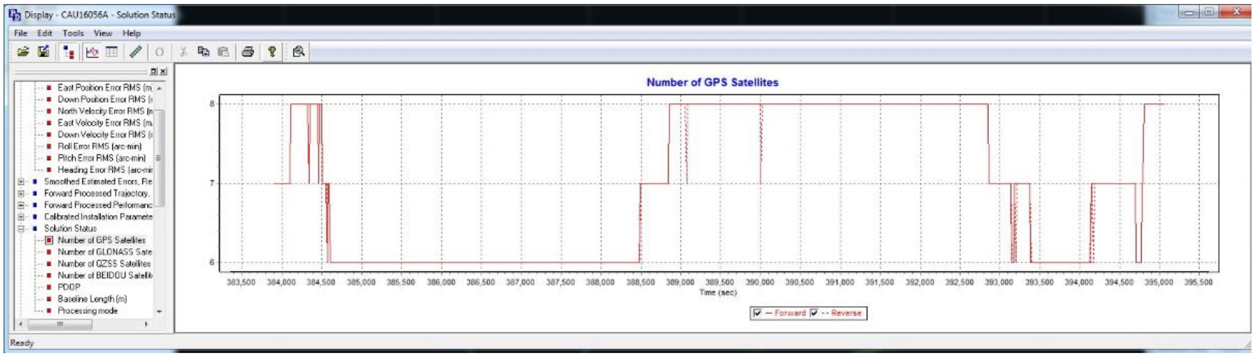


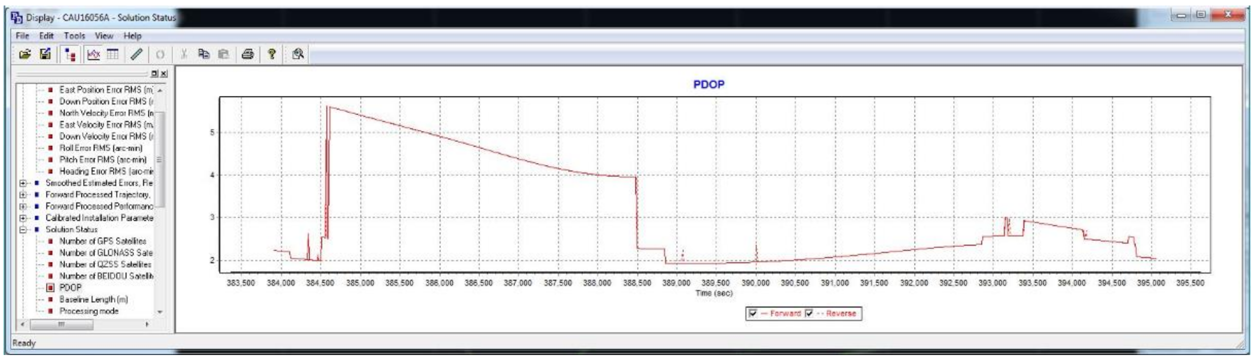

Number of GPS Satellites

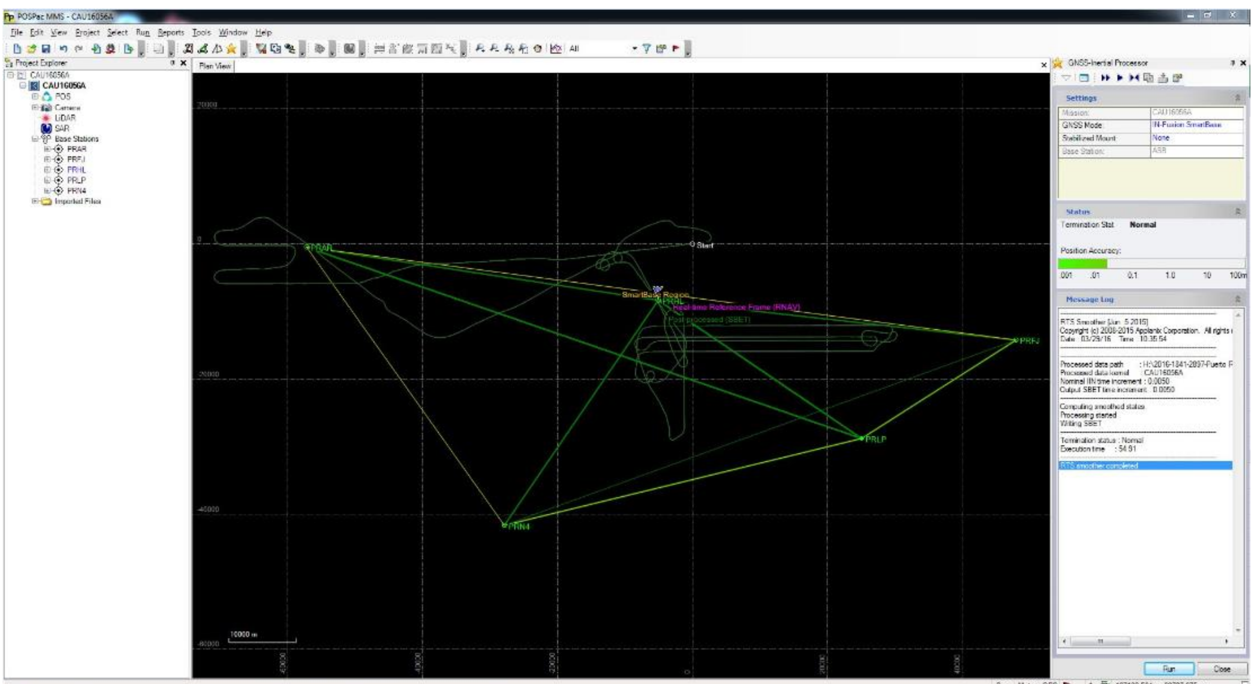

Display - CAU16050A - Solution Status
PDOP
Time (sec)
Forward
Reverse

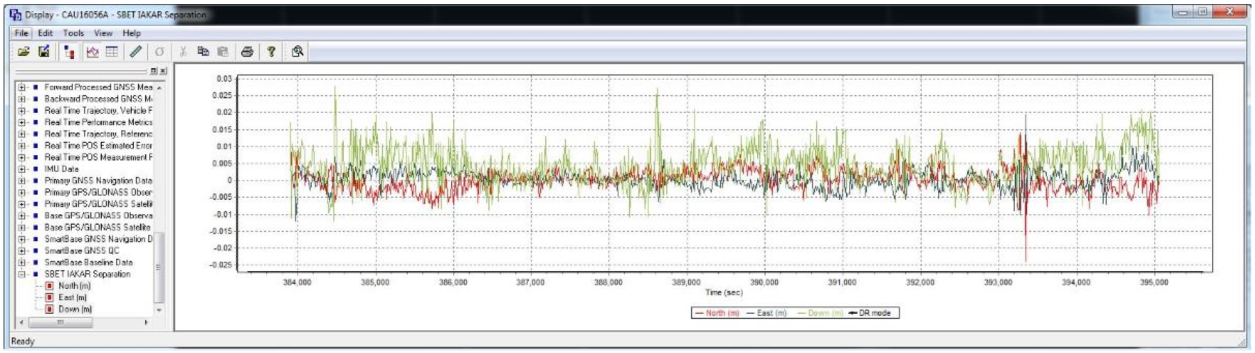

POSPac MMS - CAU16050A
Project Explorer
GNSS-Inertial Processor
Settings
Status
Termination Stat
Normal
Position Accuracy:
Message Log
Start
10000 m

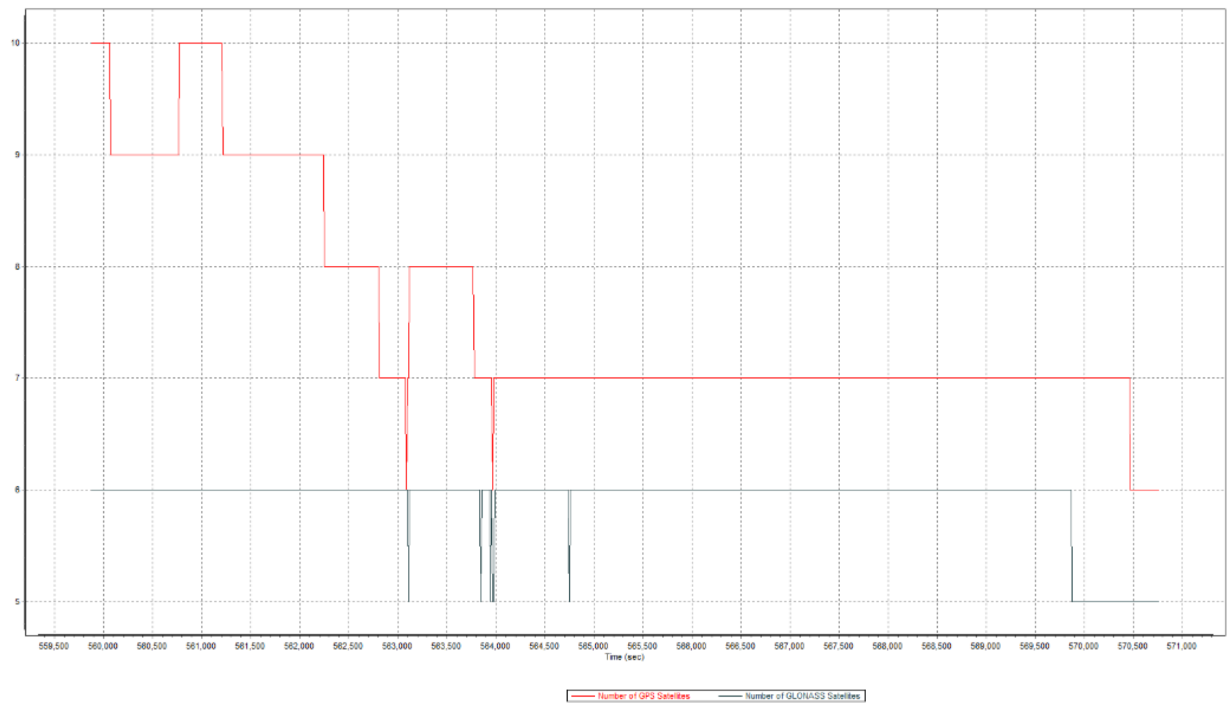

Display - CAU16050A - SBET IAKAR Separation
Time (sec)
North (m)
East (m)
Down (m)
DR mode

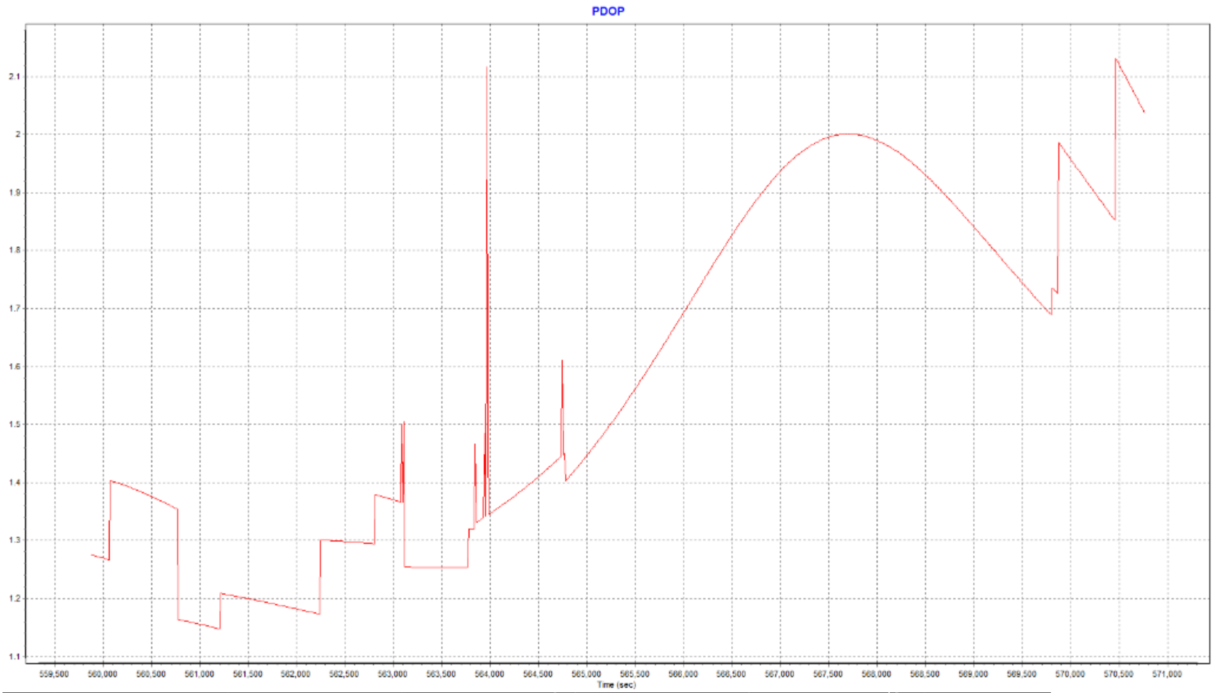

Display - CAU16056A - Solution Status
Number of GPS Satellites
Time (sec)
Forward
Reverse
Ready

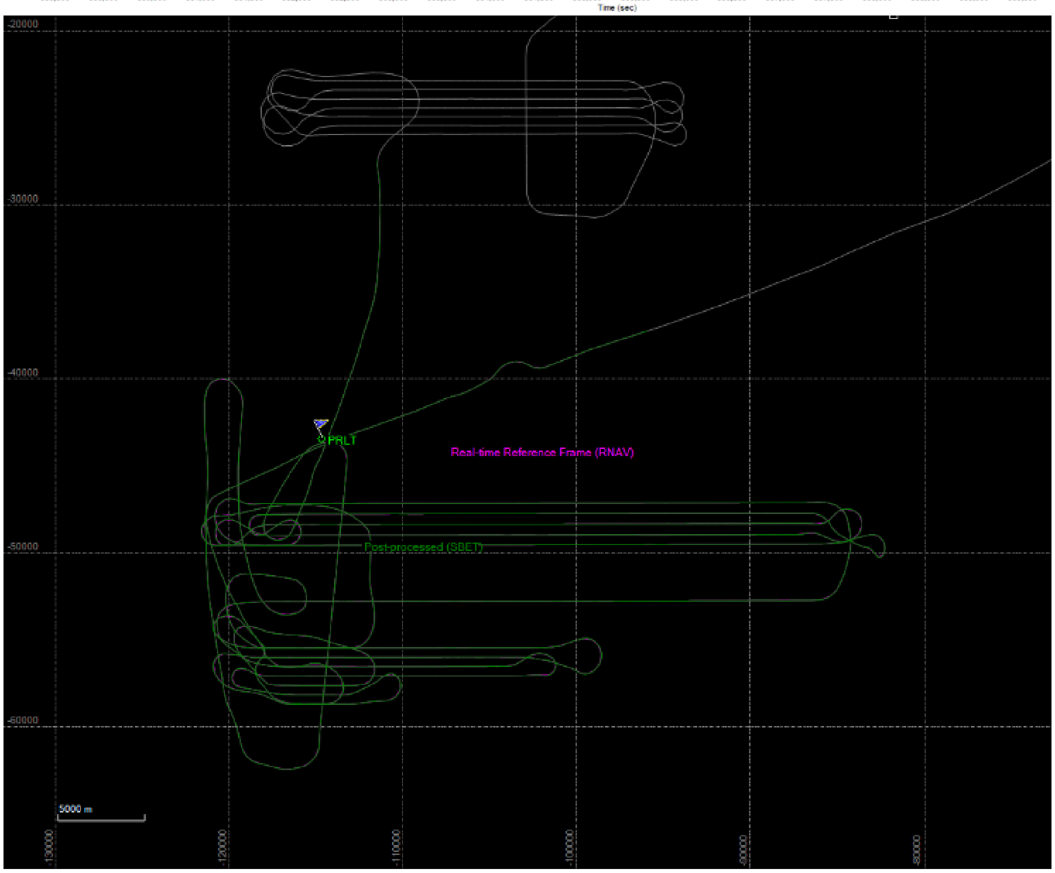

Display - CAU16056A - Solution Status
PDOP
Time (sec)
Forward
Reverse
Ready

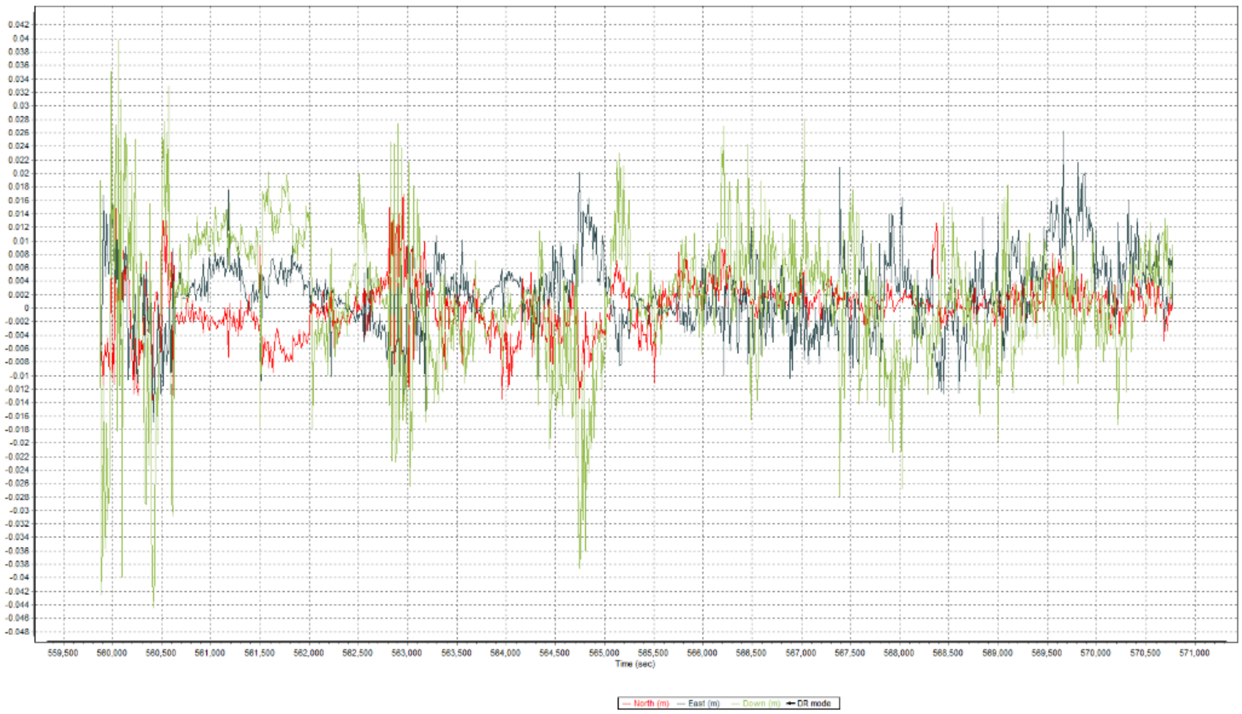

POSPac MMS - CAU16056A
Project Explorer
Plan View
GNSS-Inertial Processor
PRAR
PRFJ
PRLP
PRN4
Settings
Status
Message Log
Run
Close

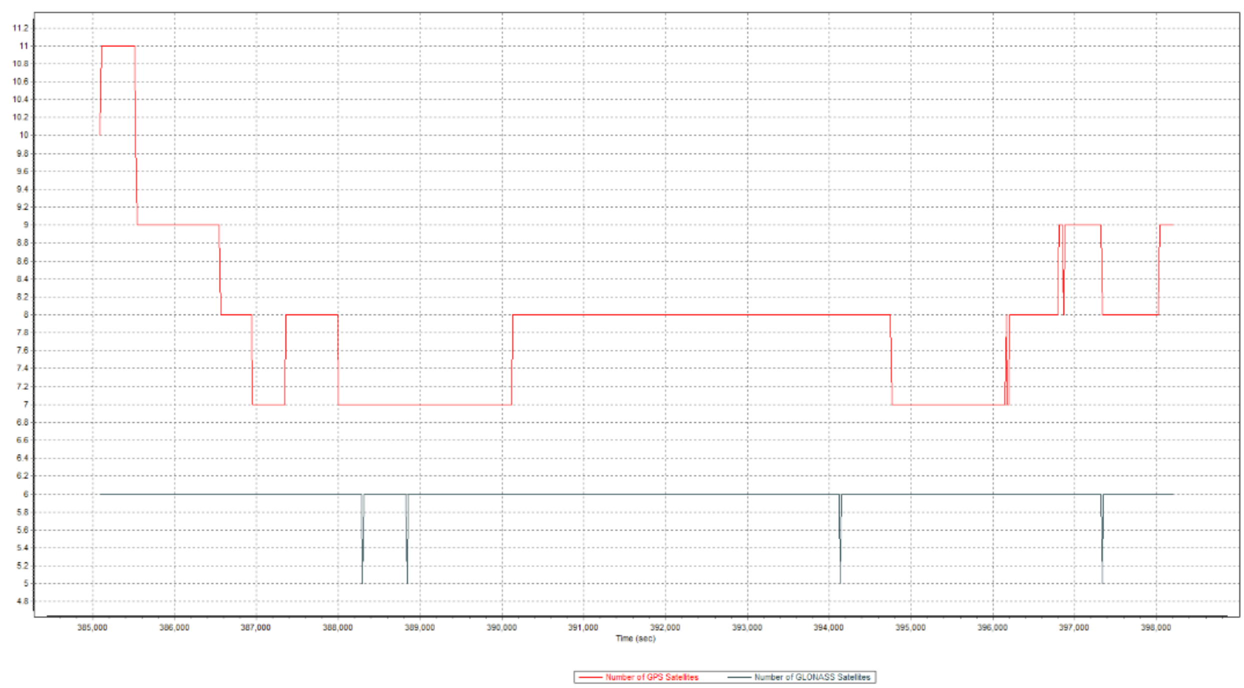

Display - CAU16056A - SBET IAKAR Separation
Time (sec)
North (m)
East (m)
Down (m)
DR mode

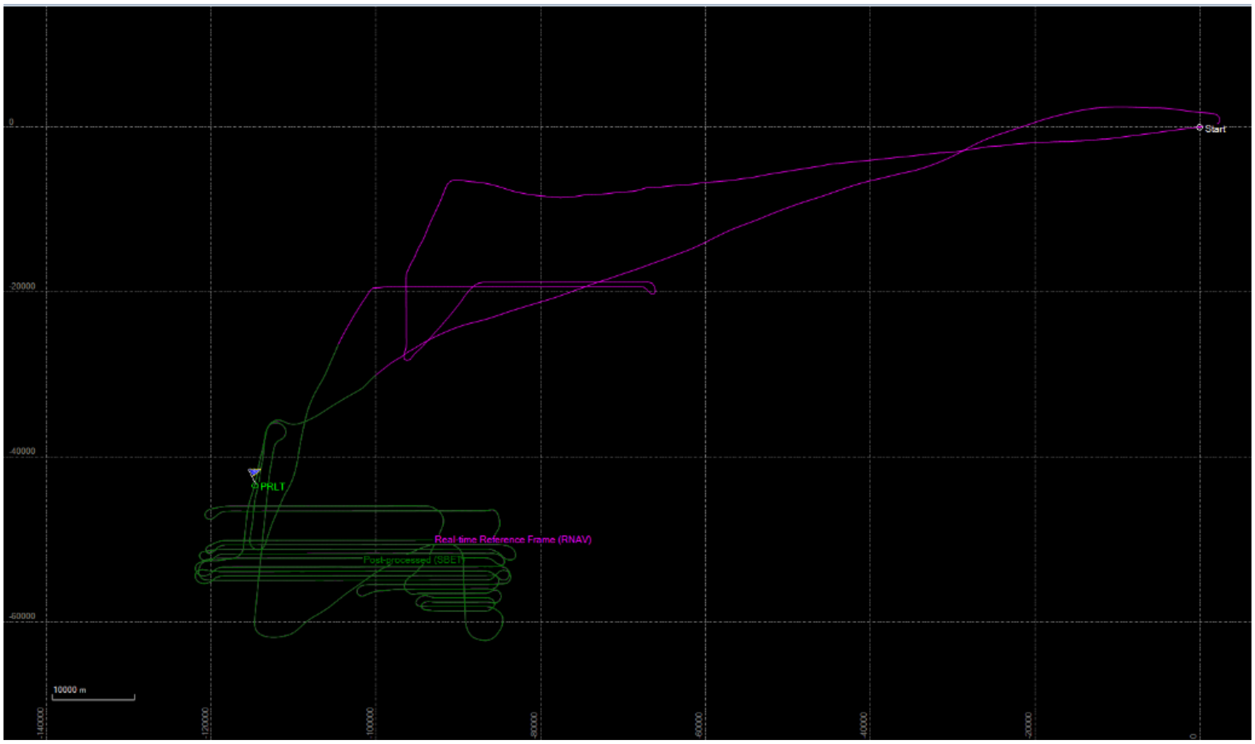

Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites


PDOP
Time (sec)


PRLT
Real-time Reference Frame (RNAV)
Post-processed (SBET)
5000 m


Time (sec)
North (m)
East (m)
Down (m)
DR mode


Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites


Start
PRLT
Real-time Reference Frame (RNAV)
Post-processed (SBET)
10000 m
0
-20000
-40000
-60000
-140000
-120000
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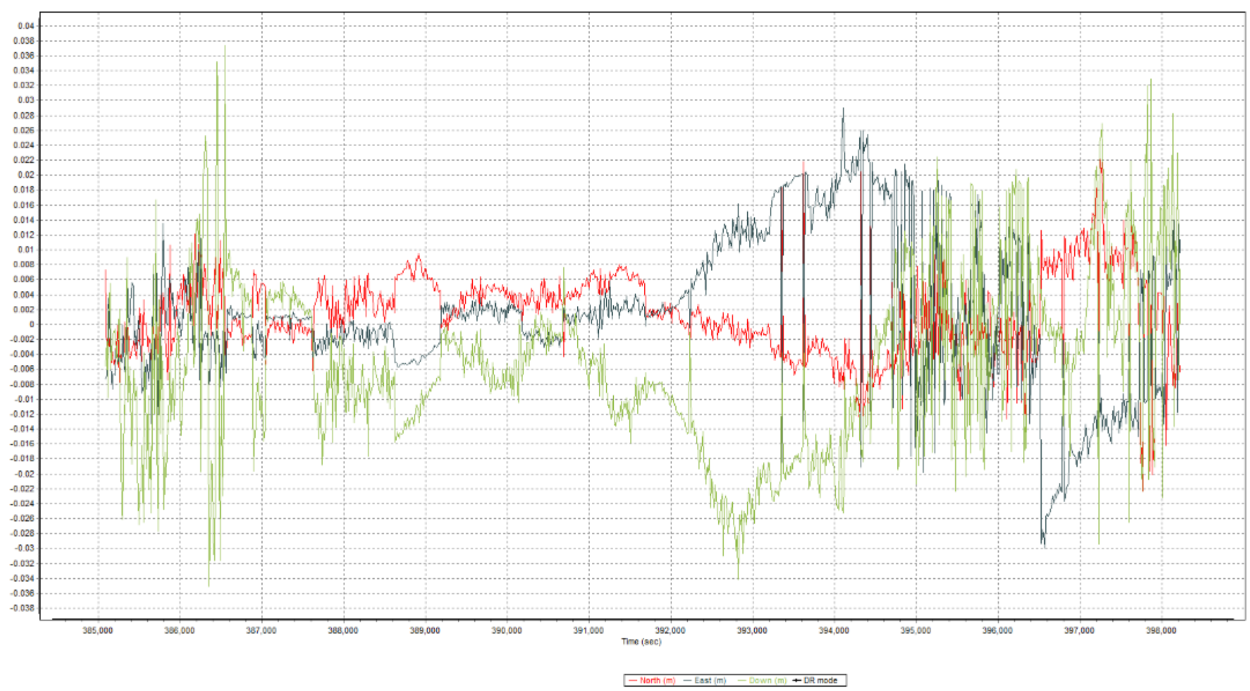
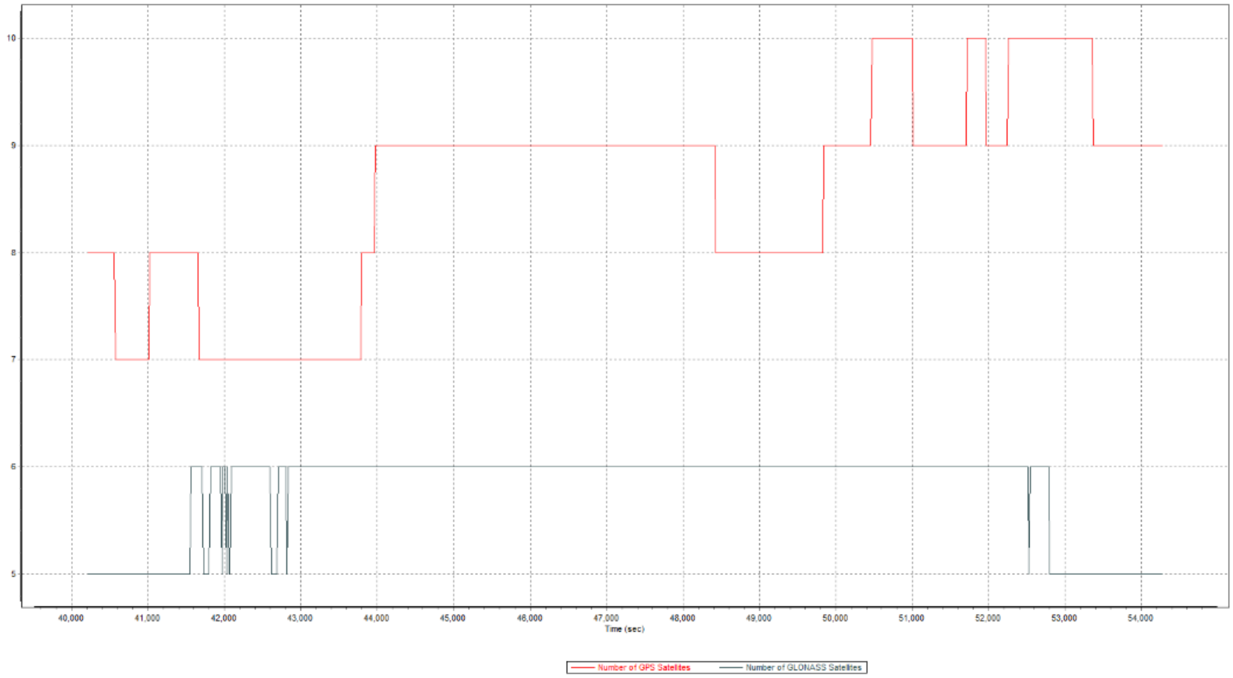
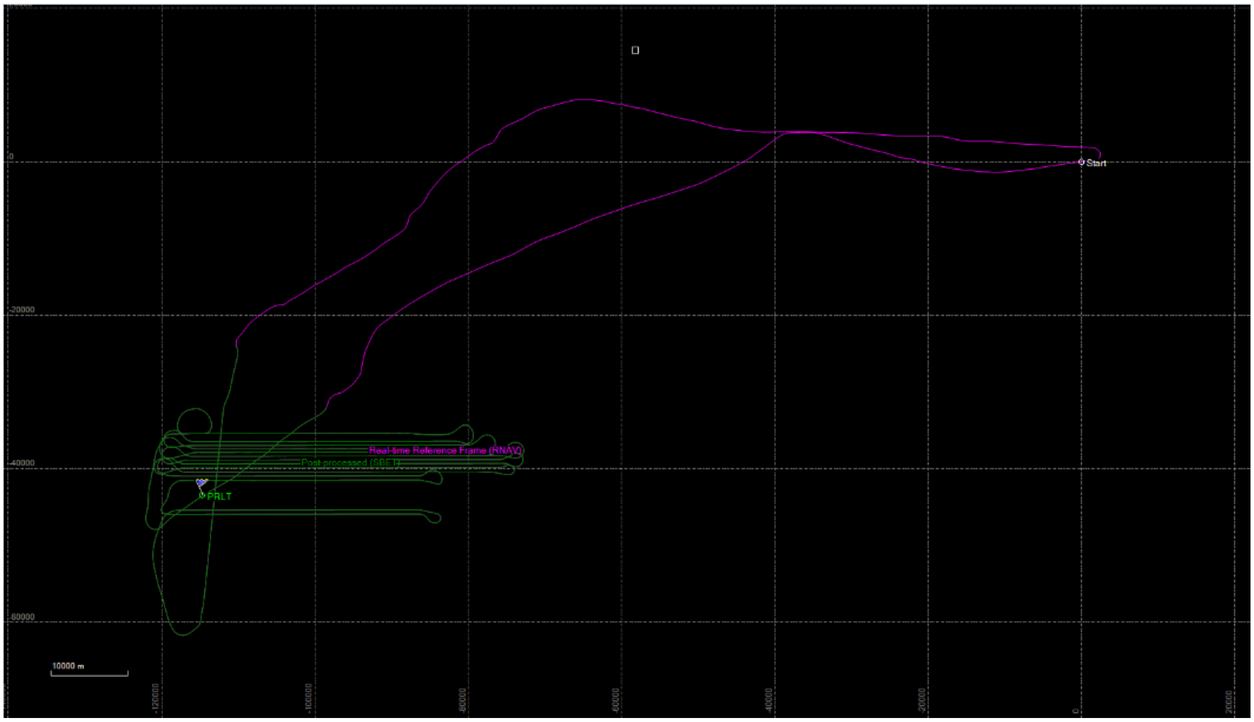
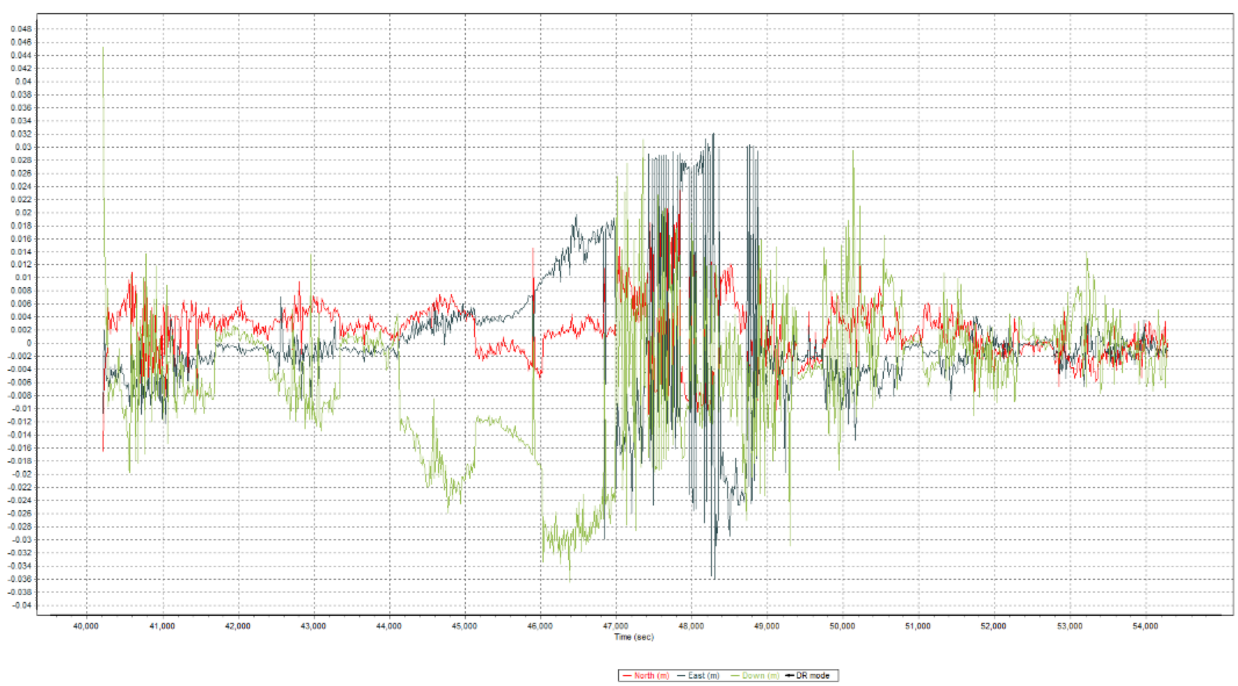
-80000
-60000
-40000
-20000
0

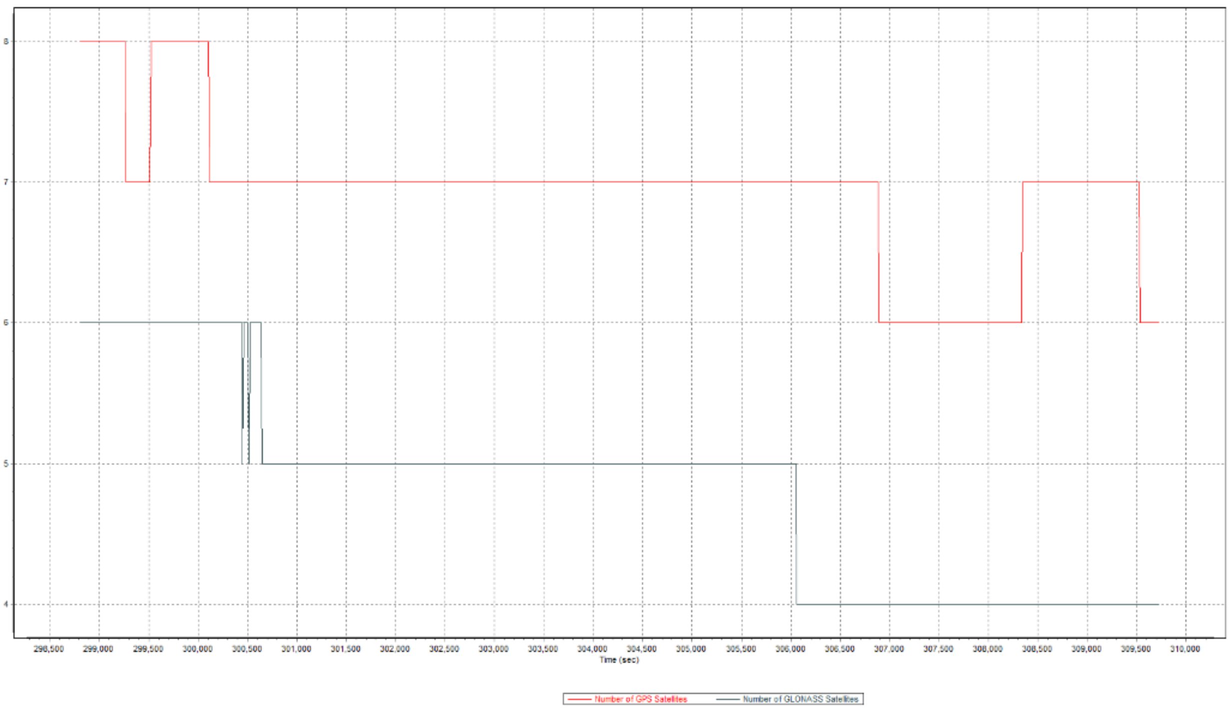

0.04
0.02
0
-0.02
-0.038
385,000
386,000
387,000
388,000
389,000
390,000
391,000
392,000
393,000
394,000
395,000
396,000
397,000
398,000
Time (sec)
North (m)
East (m)
Down (m)
DR mode


10
9
8
7
6
5
40,000
41,000
42,000
43,000
44,000
45,000
46,000
47,000
48,000
49,000
50,000
51,000
52,000
53,000
54,000
Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites

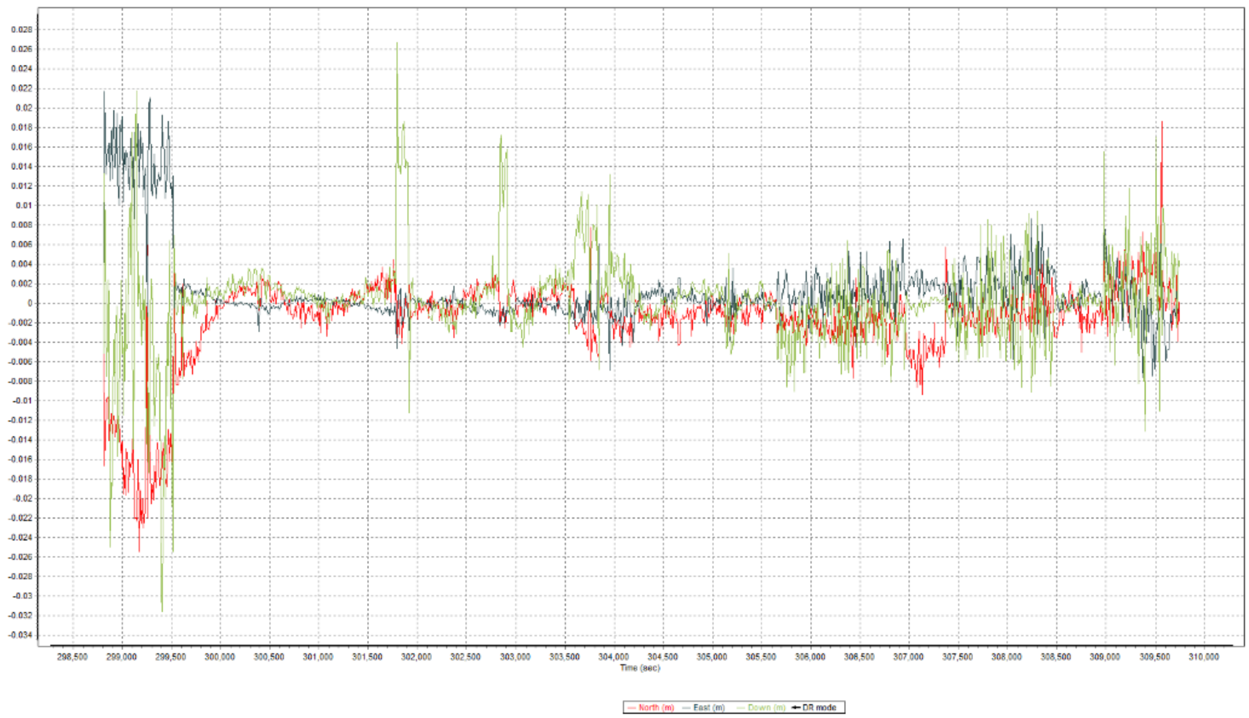

PDOP
40,000
41,000
42,000
43,000
44,000
45,000
46,000
47,000
48,000
49,000
50,000
51,000
52,000
53,000
54,000
Time (sec)

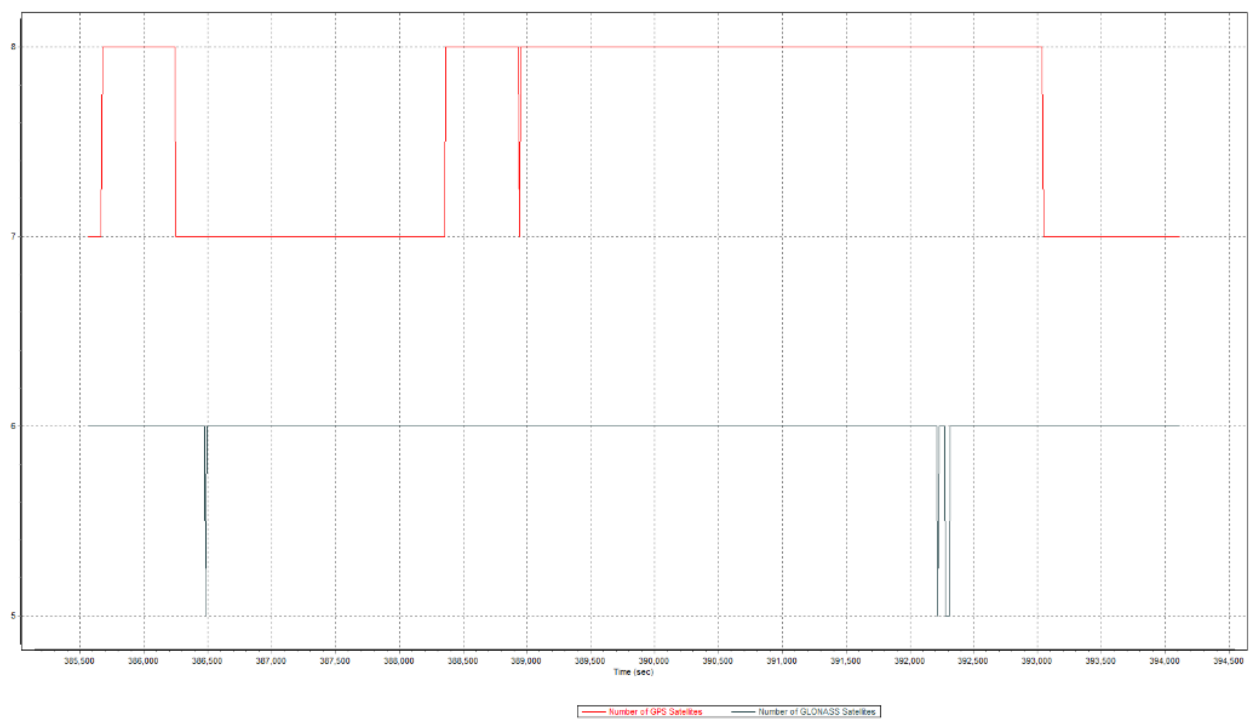

Start
PRLT
Real-time Reference Frame (RNAV)
10000 m

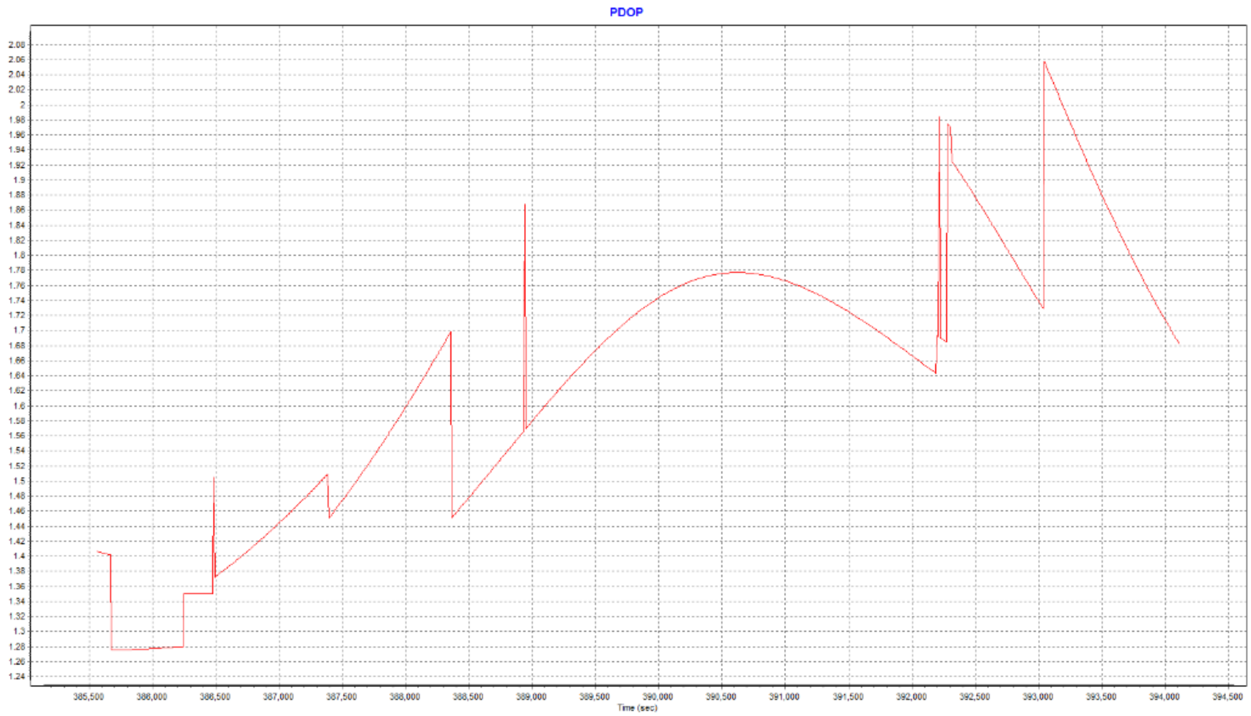

Time (sec)
North (m)
East (m)
Down (m)
DR mode

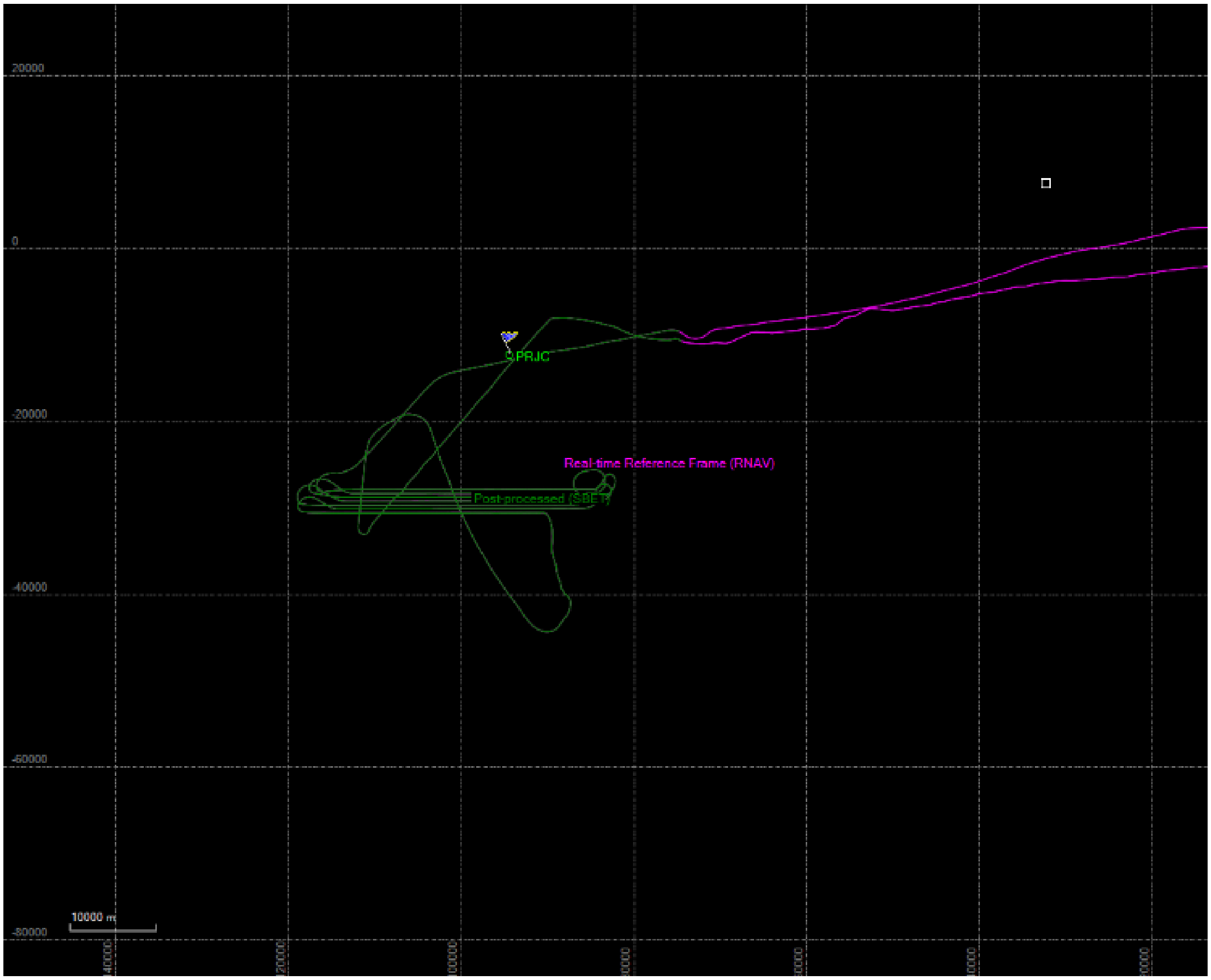

Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites

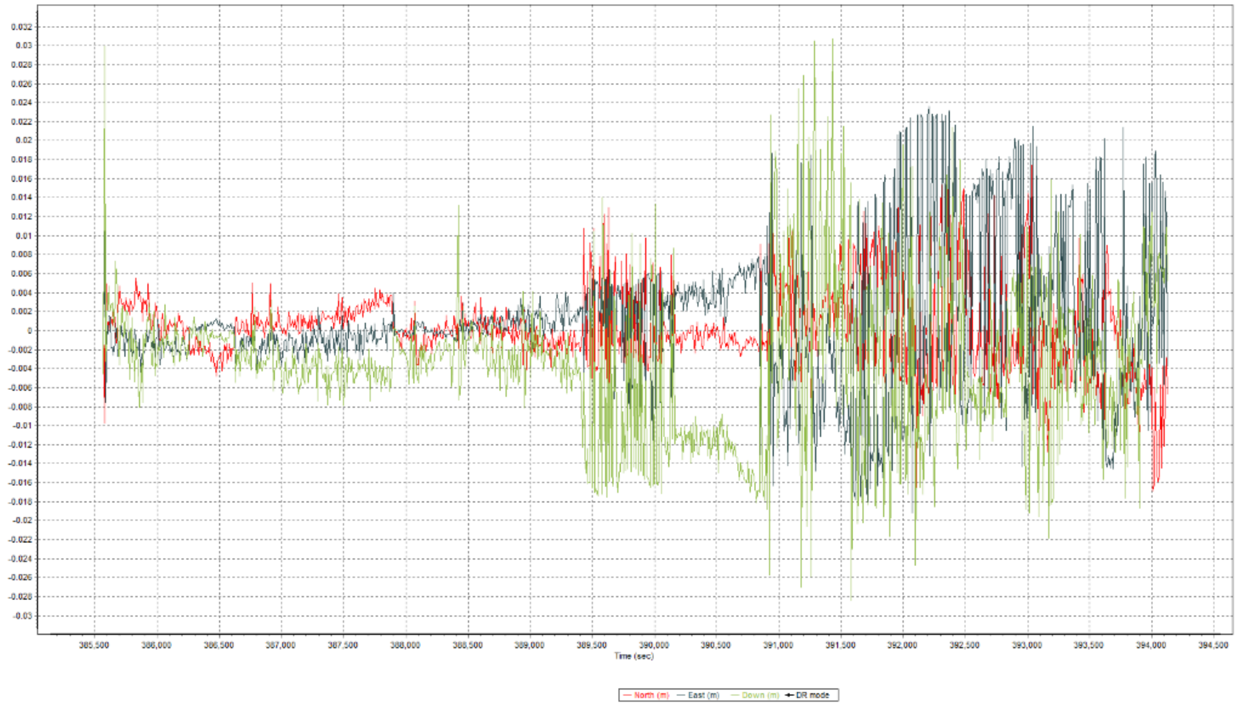

PDOP
Time (sec)

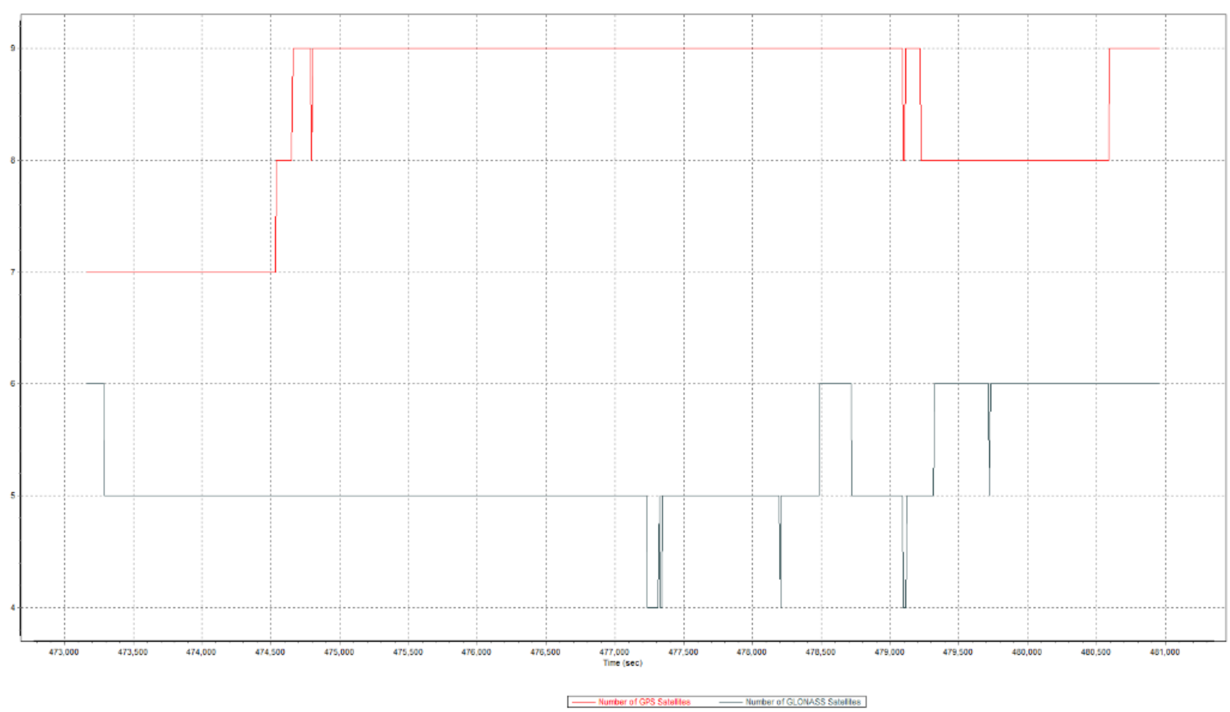

Time (sec)
North (m)
East (m)
Down (m)
DR mode

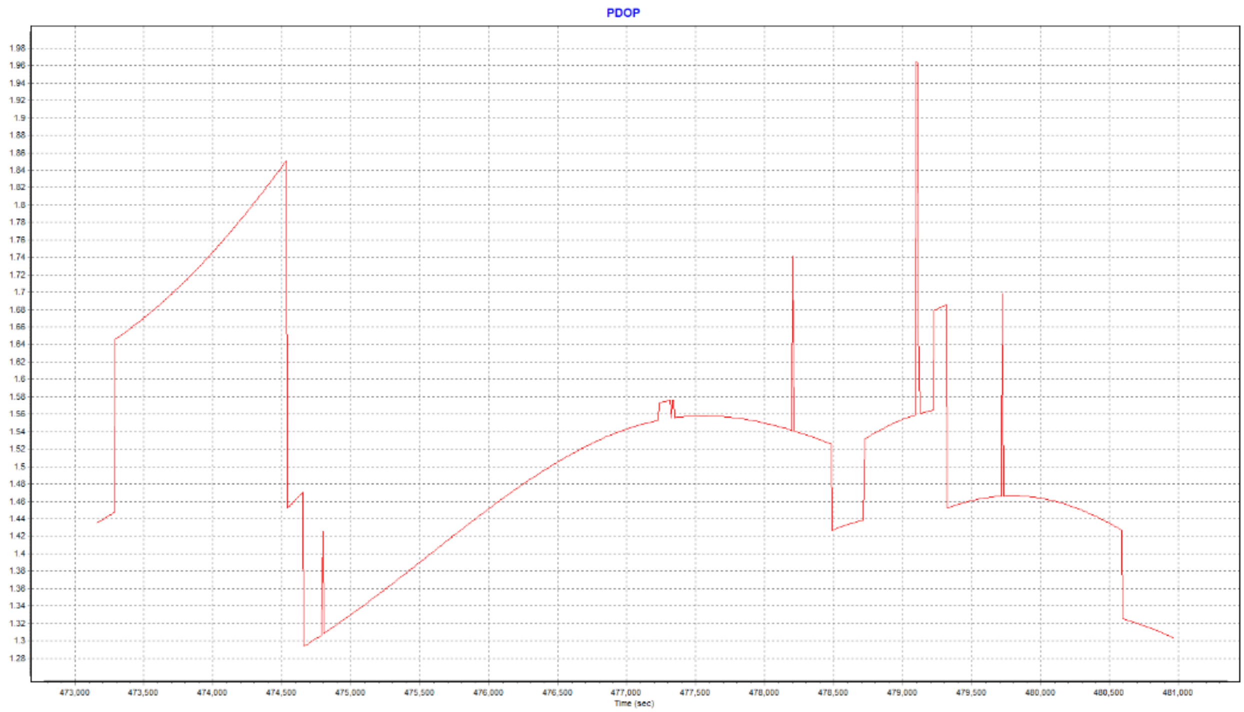

Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites

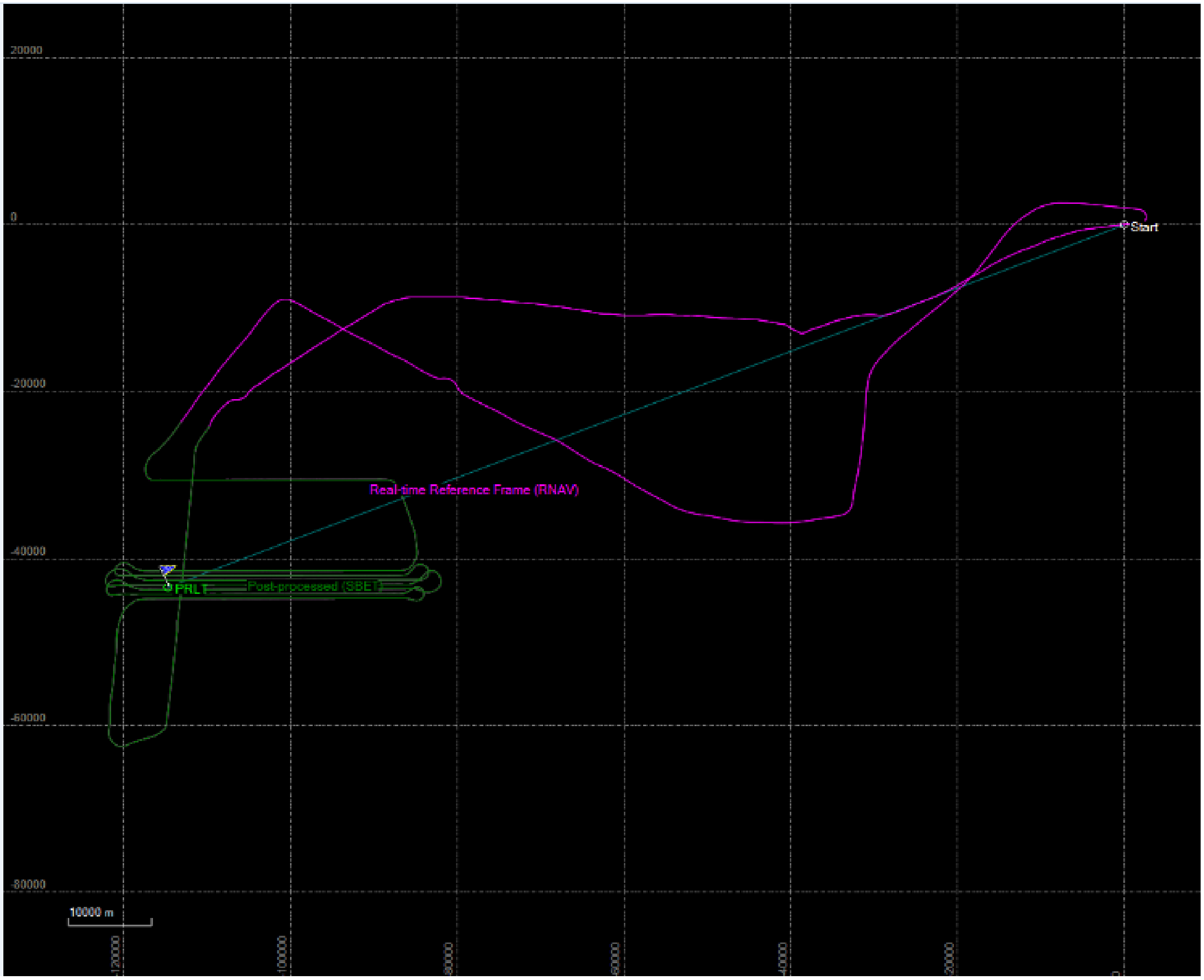

PDOP
Time (sec)

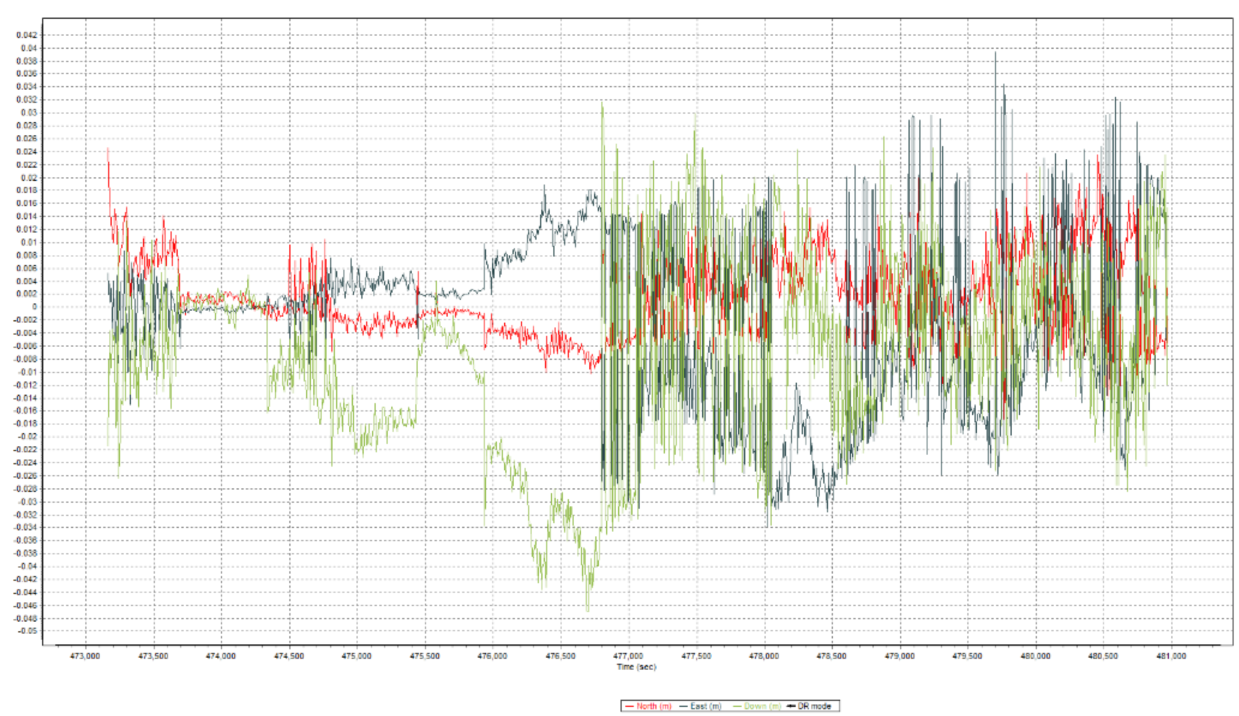

20000
0
-20000
-40000
-60000
-80000
10000 m
PRJC
Real-time Reference Frame (RNAV)
Post-processed (SBET)

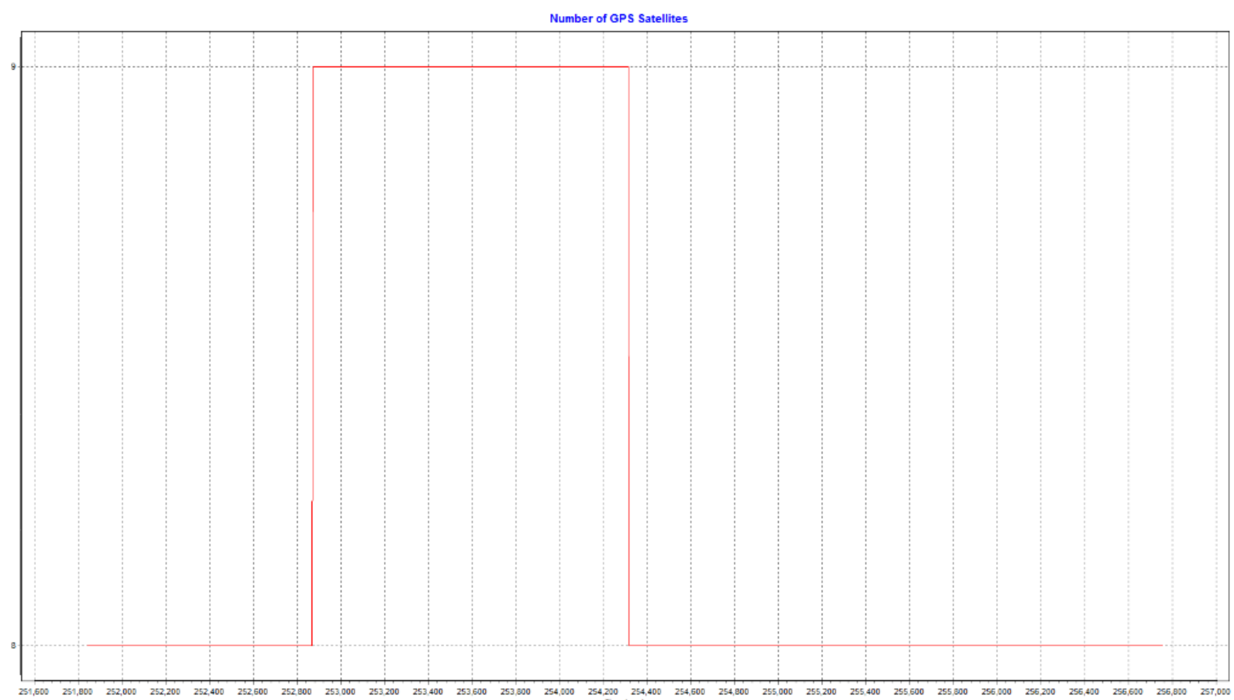

Time (sec)
385,500
386,000
386,500
387,000
387,500
388,000
388,500
389,000
389,500
390,000
390,500
391,000
391,500
392,000
392,500
393,000
393,500
394,000
394,500
North (m)
East (m)
Down (m)
DR mode

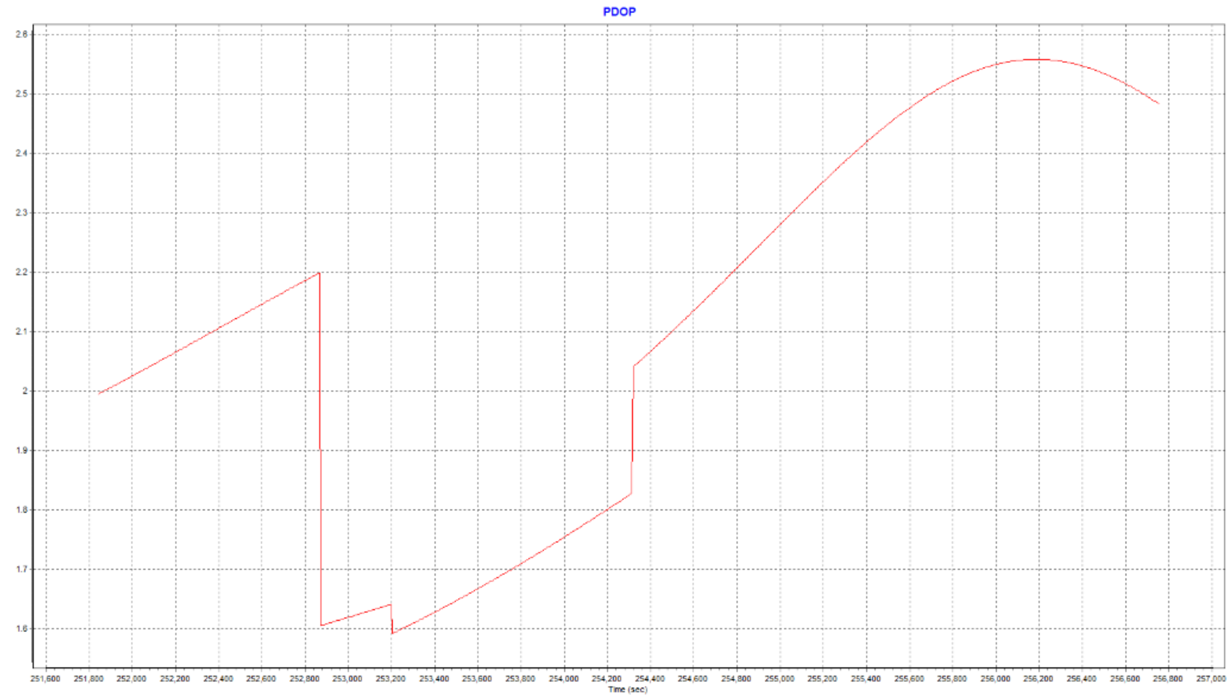

9
8
7
6
5
4
473,000
473,500
474,000
474,500
475,000
475,500
476,000
476,500
477,000
477,500
478,000
478,500
479,000
479,500
480,000
480,500
481,000
Time (sec)
Number of GPS Satellites
Number of GLONASS Satellites

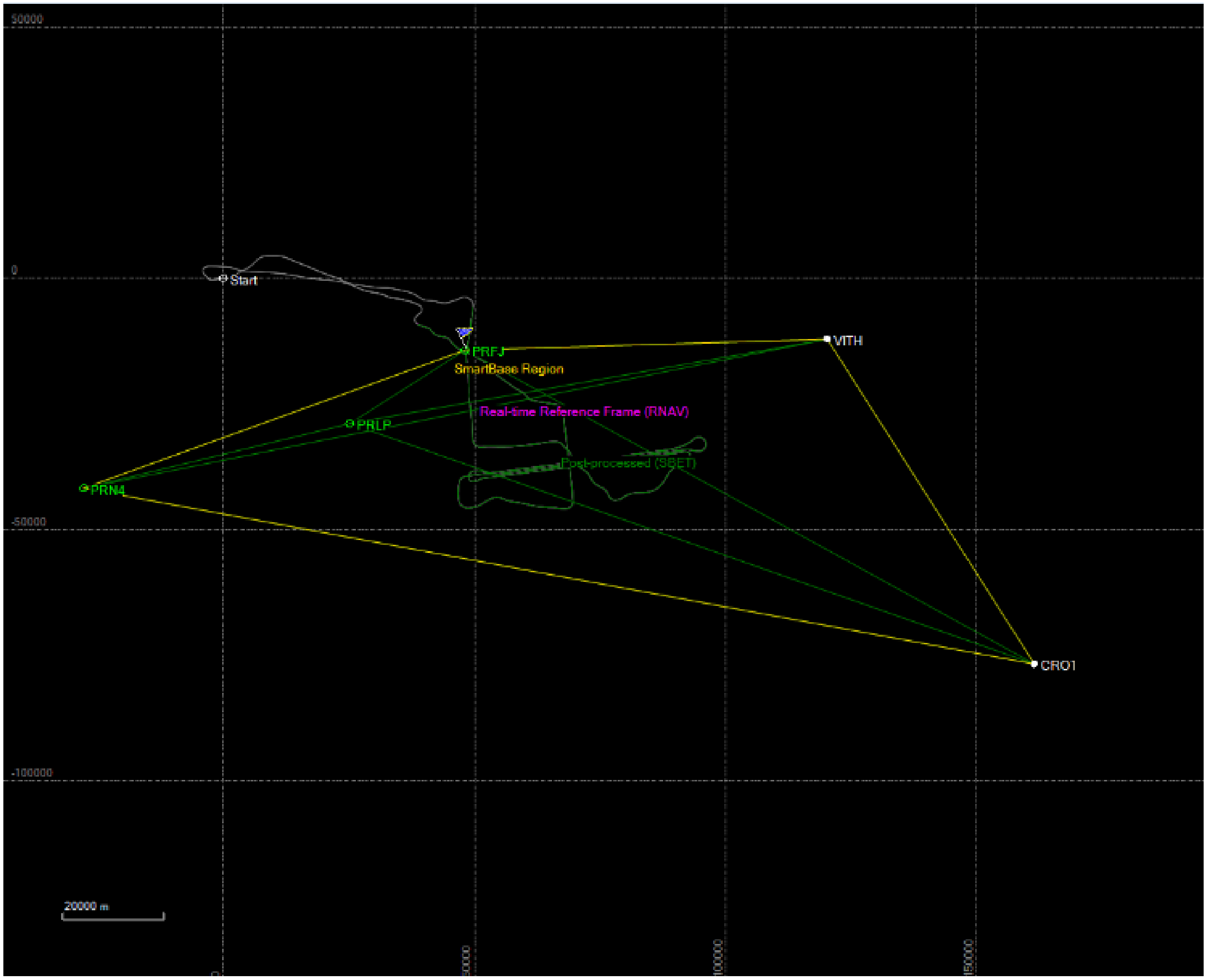

PDOP
Time (sec)

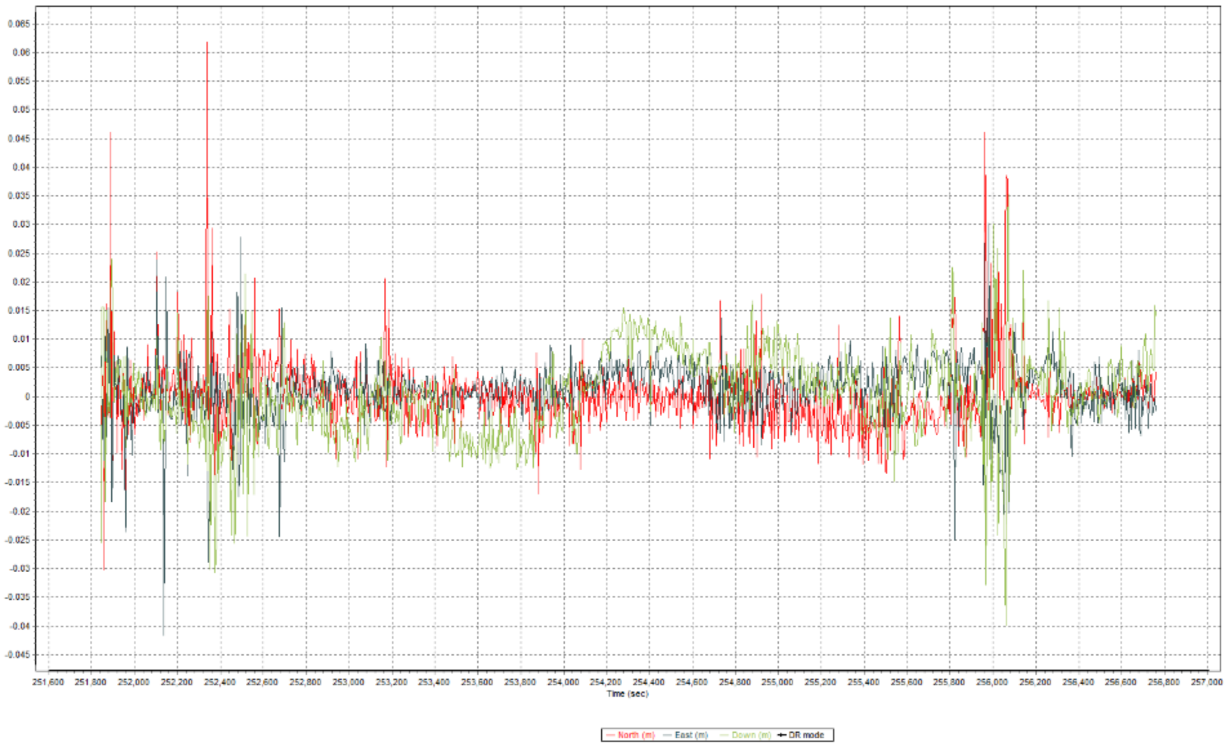

20000
0
-20000
-40000
-60000
-80000
10000 m
Start
Real-time Reference Frame (RNAV)
PRLT
Post-processed (SBET)


Time (sec)
North (m)
East (m)
Down (m)
DR mode

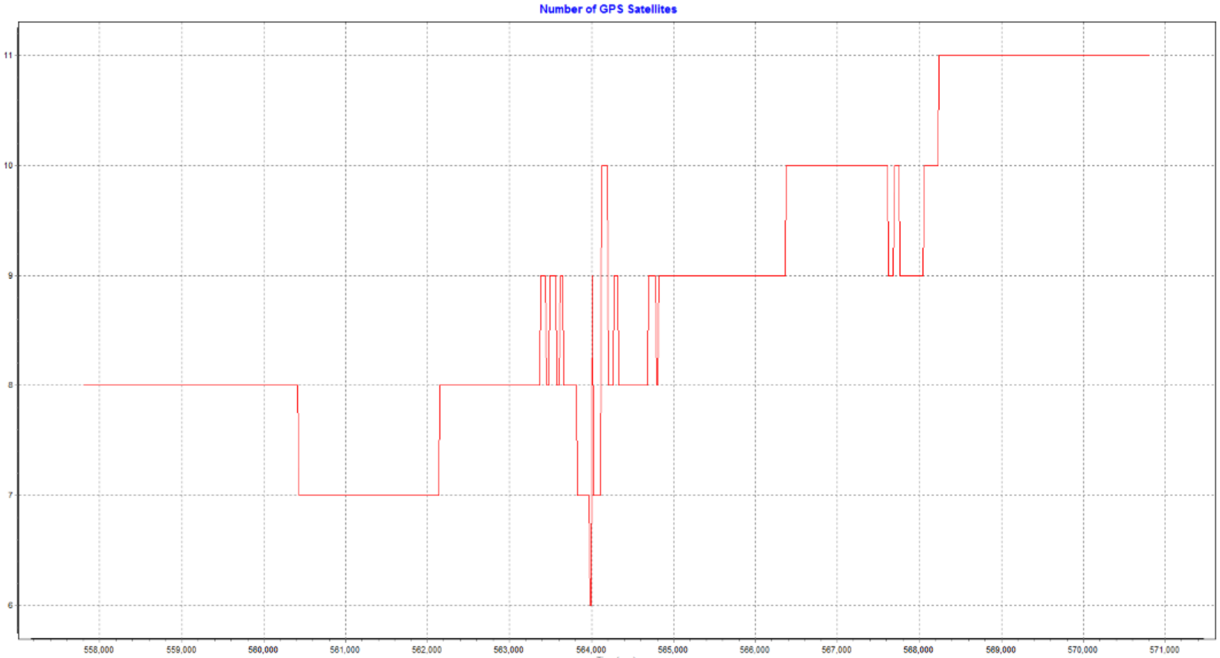

Number of GPS Satellites
Time (sec)

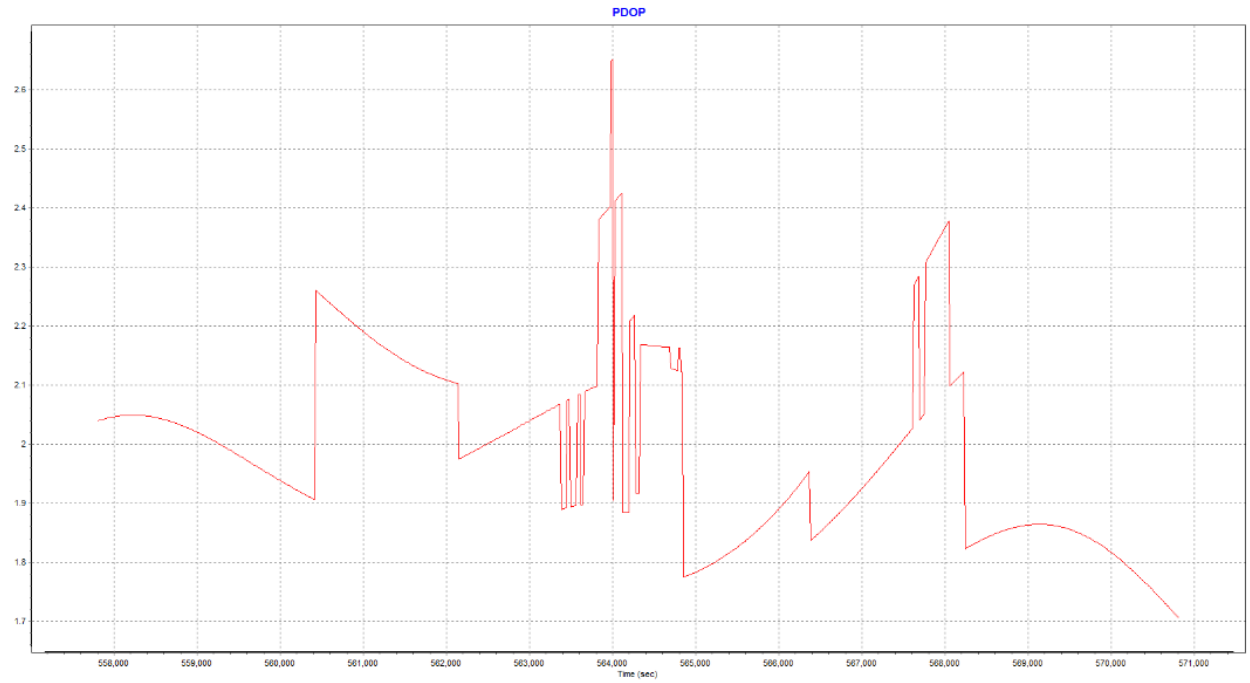

PDOP
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
251,600
251,800
252,000
252,200
252,400
252,600
252,800
253,000
253,200
253,400
253,600
253,800
254,000
254,200
254,400
254,600
254,800
255,000
255,200
255,400
255,600
255,800
256,000
256,200
256,400
256,600
256,800
257,000
Time (sec)

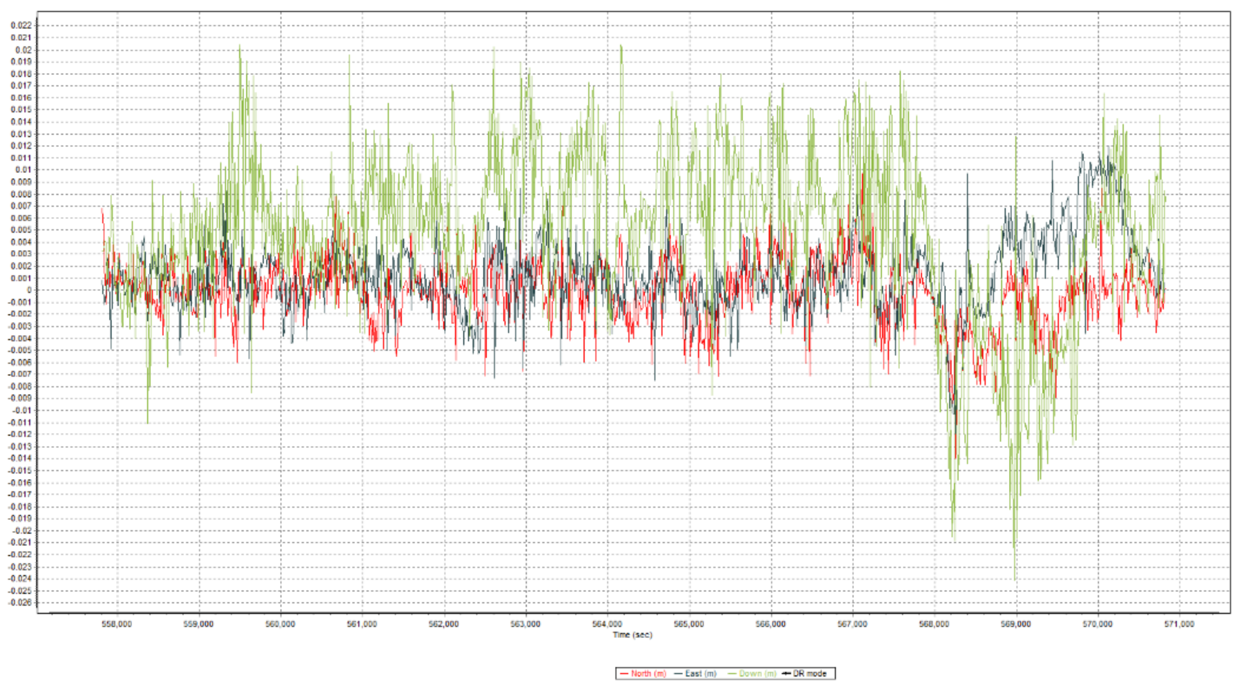

50000
0
-50000
-100000
Start
PRFJ
SmartBase Region
VITH
Real-time Reference Frame (RNAV)
PRLP
Post-processed (SBET)
PRN4
CRO1
20000 m
0
50000
100000
150000

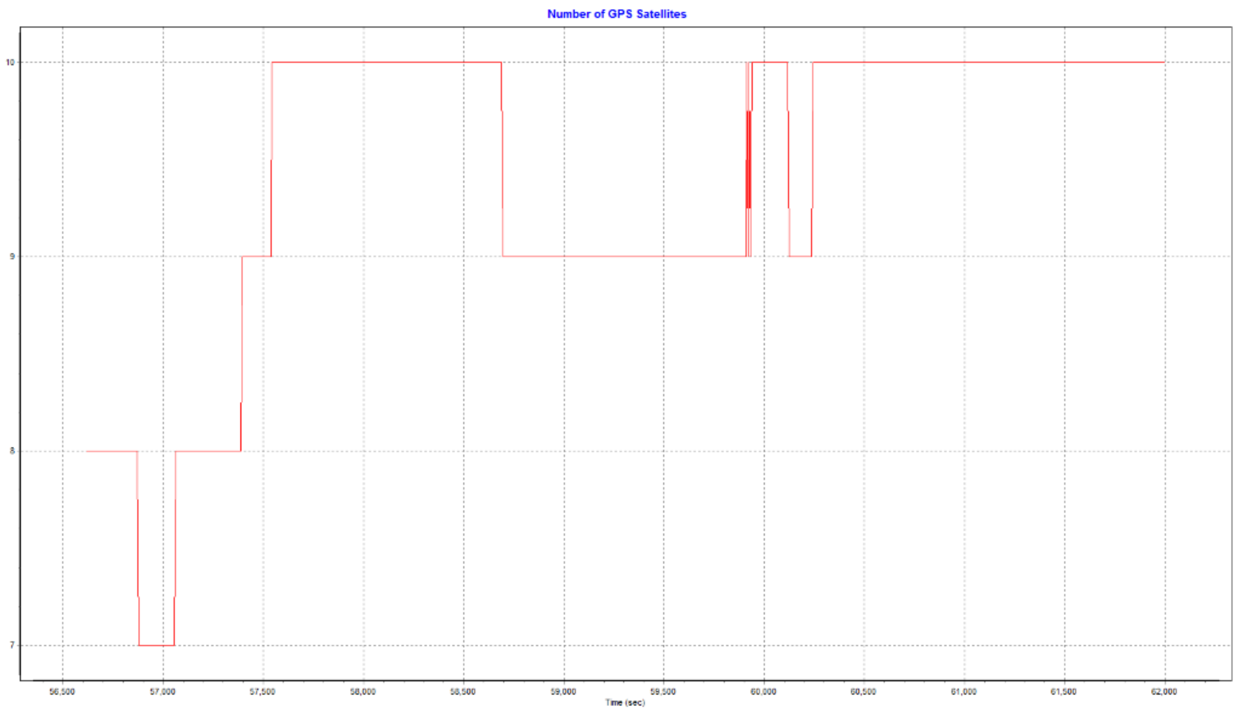


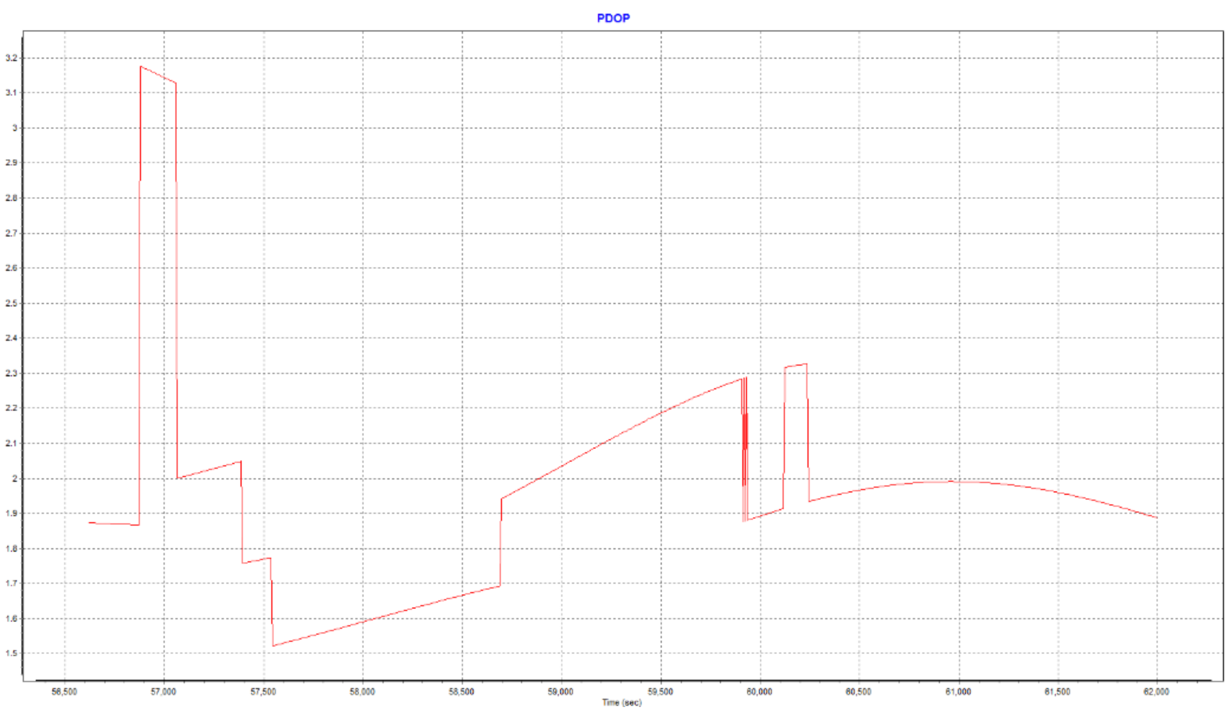
Number of GPS Satellites

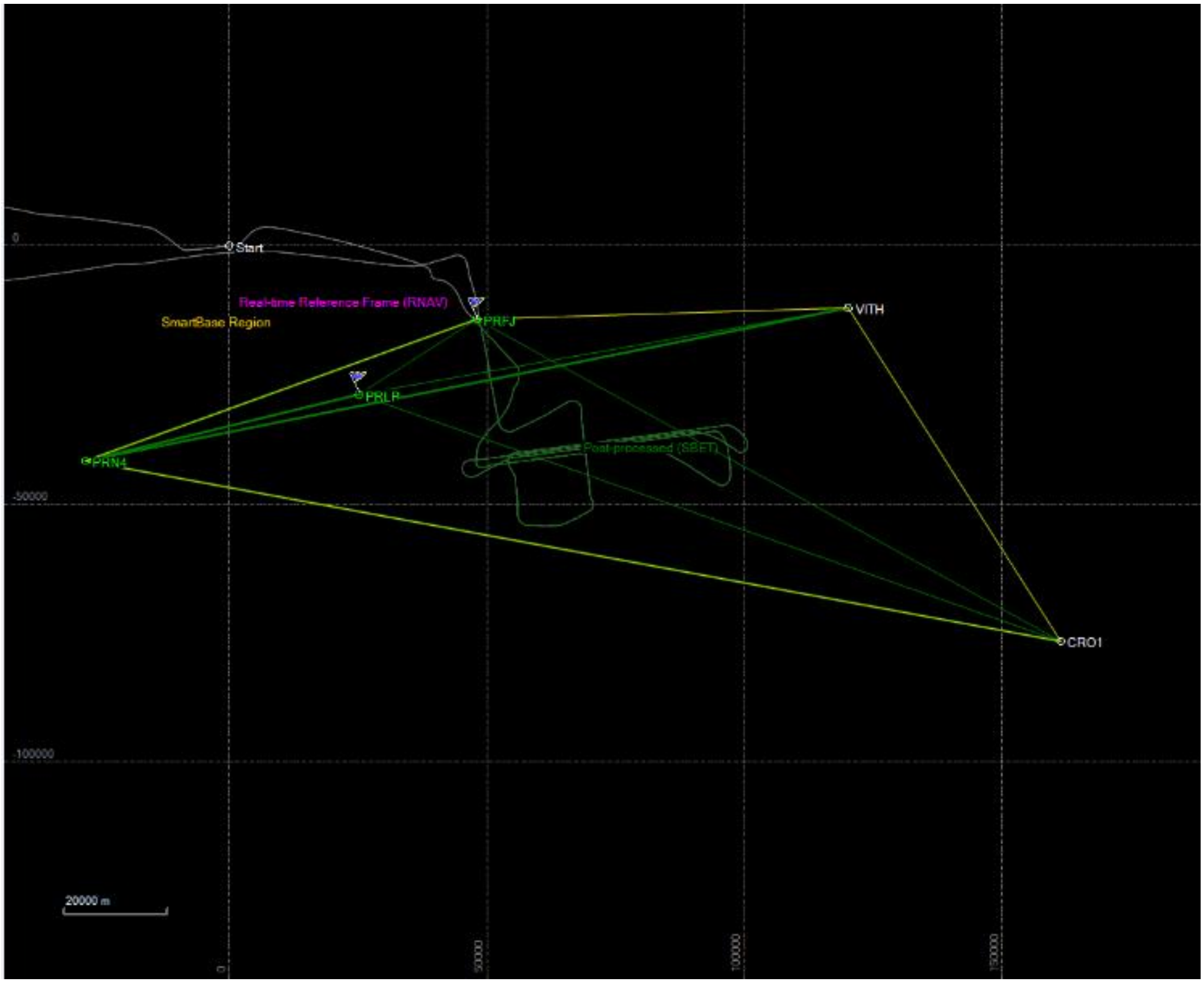


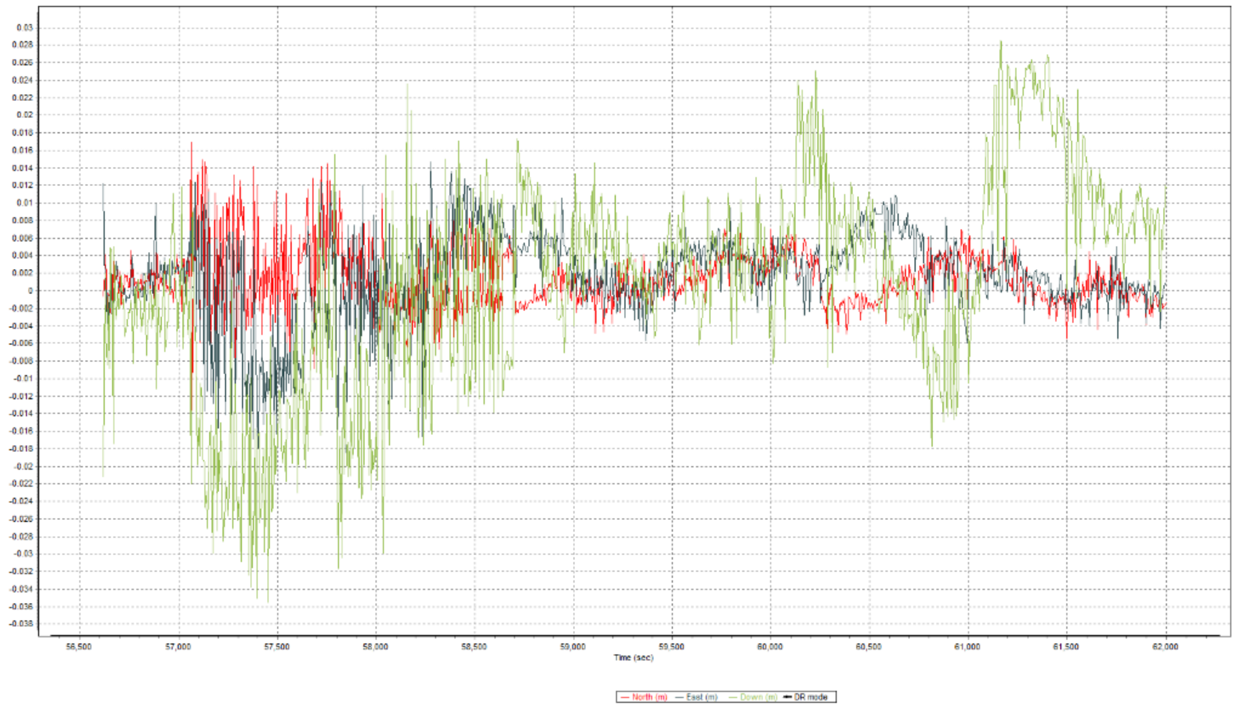

PDOP
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
558,000
559,000
560,000
561,000
562,000
563,000
564,000
565,000
566,000
567,000
568,000
569,000
570,000
571,000
Time (sec)

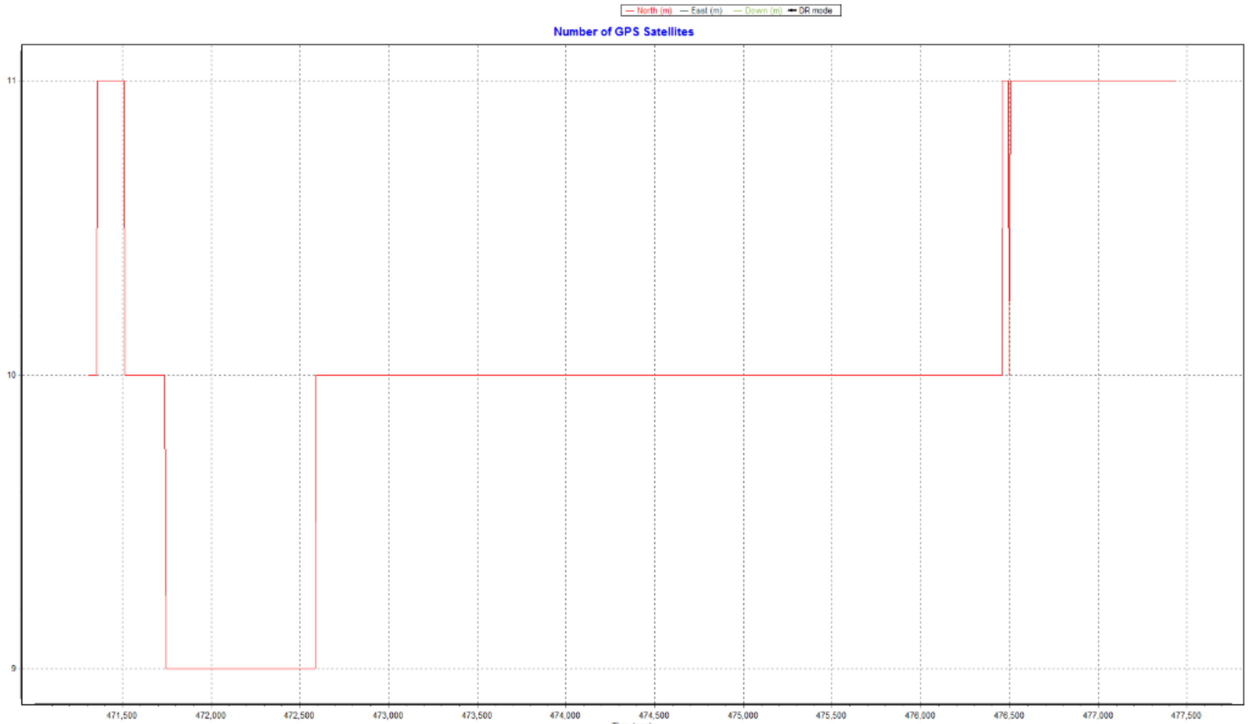

0.022
0.02
0.01
0
-0.01
-0.02
-0.026
558,000
559,000
560,000
561,000
562,000
563,000
564,000
565,000
566,000
567,000
568,000
569,000
570,000
571,000
Time (sec)
North (m)
East (m)
Down (m)
DR mode

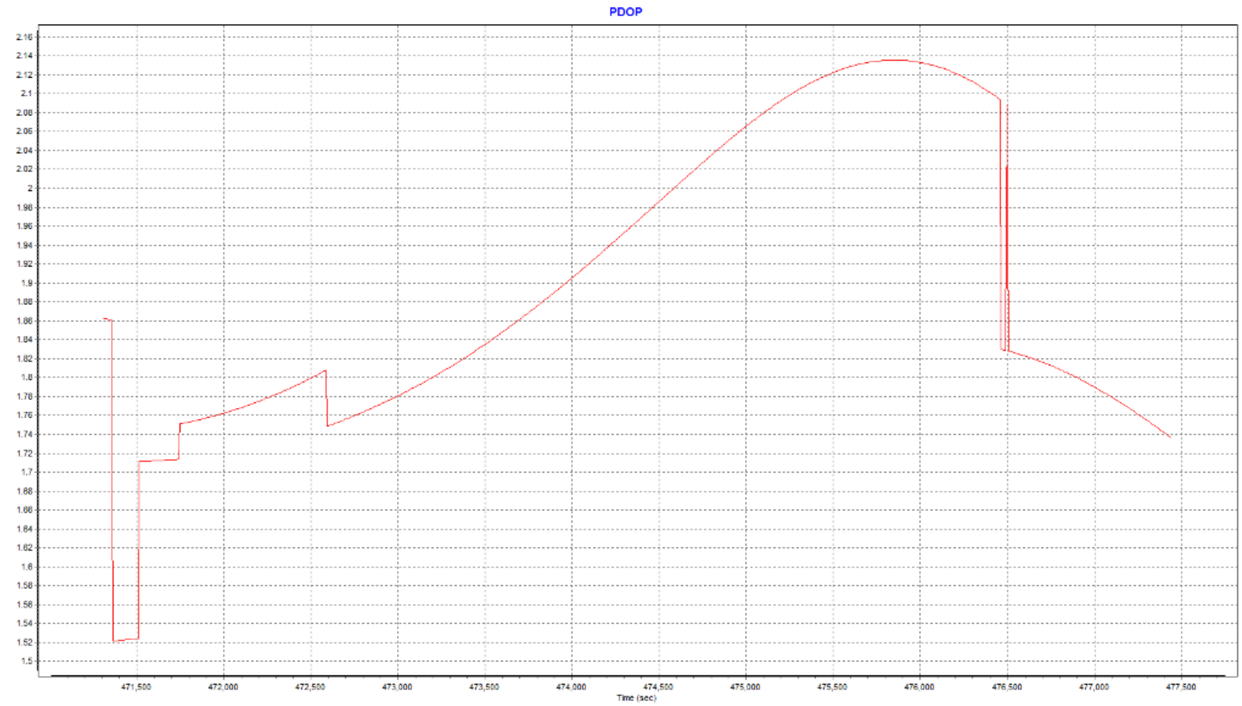

Number of GPS Satellites
10
9
8
7
56,500
57,000
57,500
58,000
58,500
59,000
59,500
60,000
60,500
61,000
61,500
62,000
Time (sec)

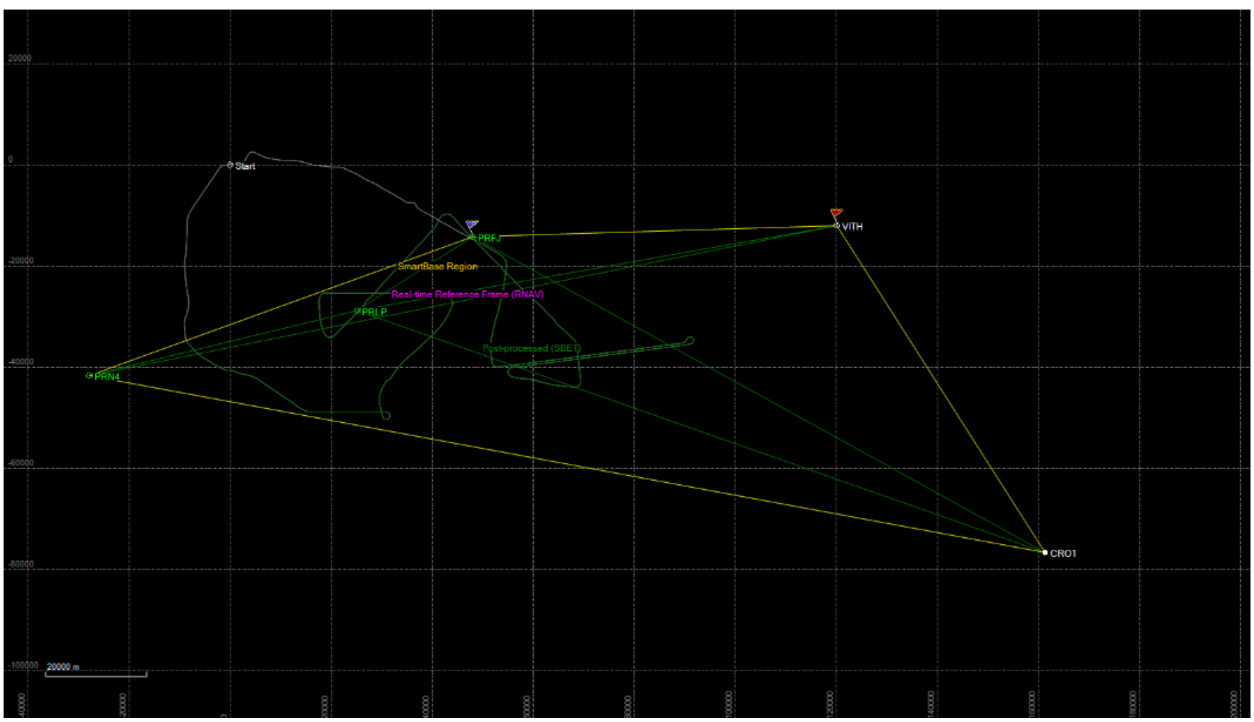

PDOP
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
56,500
57,000
57,500
58,000
58,500
59,000
59,500
60,000
60,500
61,000
61,500
62,000
Time (sec)

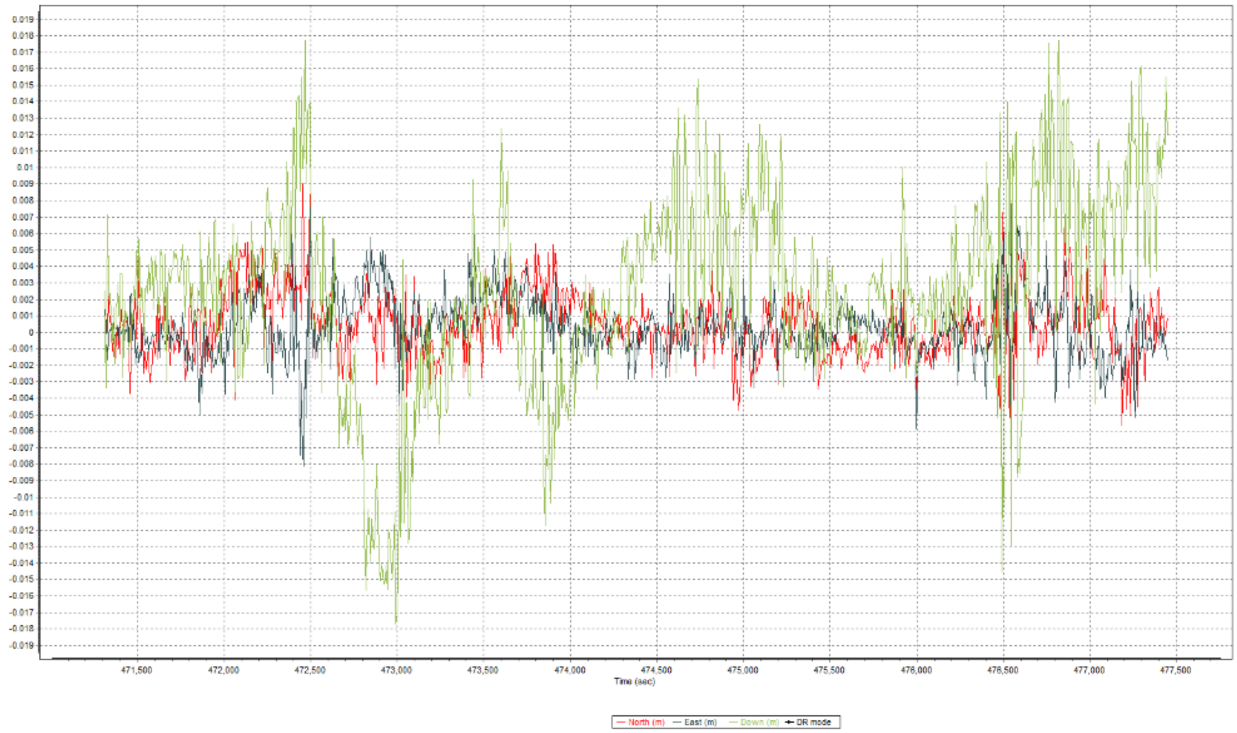

Start
Real-time Reference Frame (RNAV)
SmartBase Region
PRFJ
VITH
PRLP
PRN4
Post-processed (SBET)
CRO1
0
-50000
-100000
20000 m
0
50000
100000
150000


Time (sec)
North (m)
East (m)
Down (m)
DR mode


Number of GPS Satellites
Time (sec)


PDOP
Time (sec)


Start
PRFJ
VITH
SmartBase Region
Real-time Reference Frame (RNAV)
PRLP
Post-processed (SBET)
PRN4
CRO1
20000 m


Time (sec)
North (m)
East (m)
Down (m)
DR mode

Appendix E: Puerto Rico Topobathy Final Report of Survey

Please see the separate document delivered with this report:
Appendix_E_PuertoRico_Topobathy_Final_Report_of_Survey.pdf