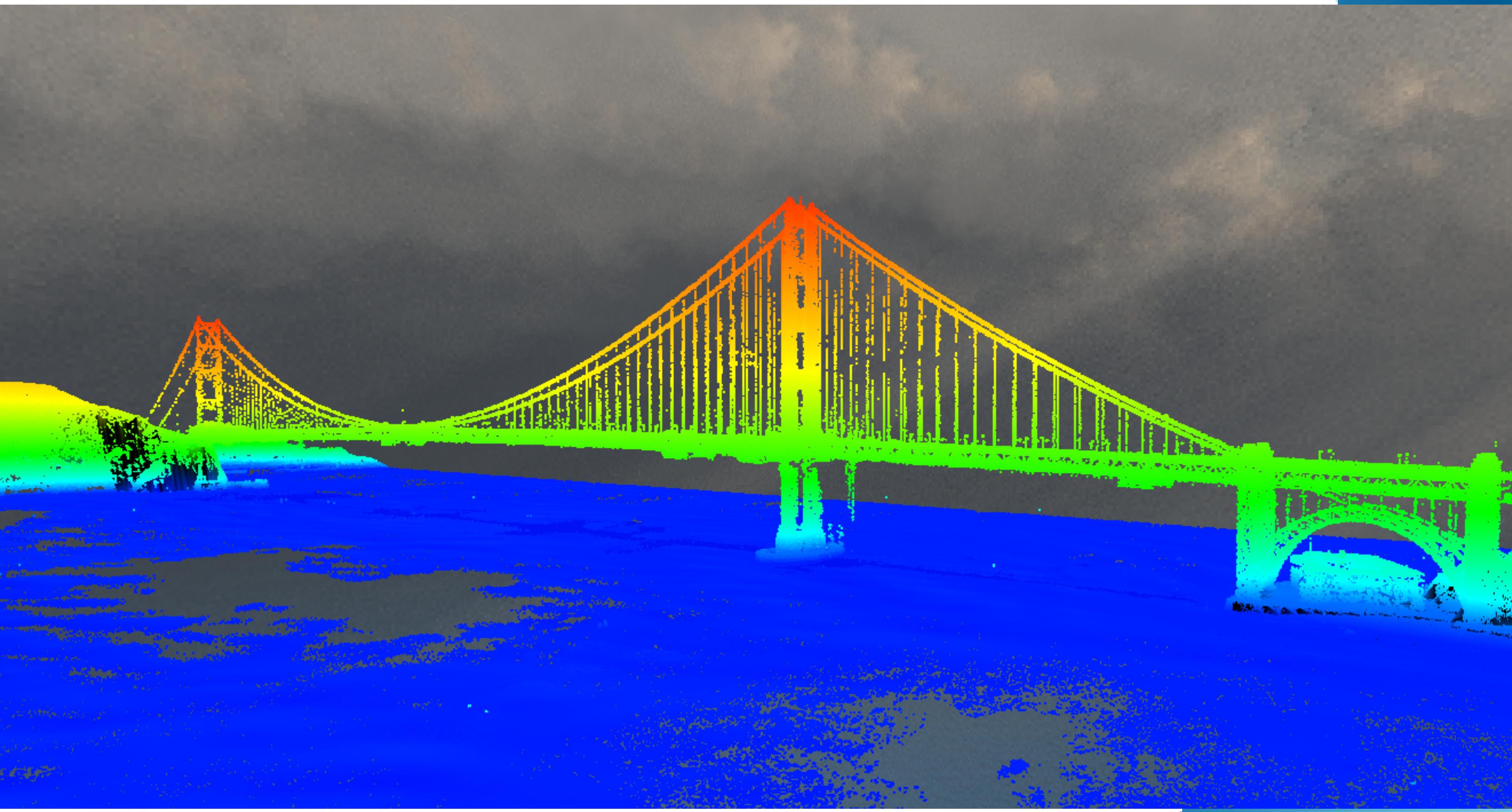
NV5 GEOSPATIAL



Submitted: February 1, 2024

CA San Francisco B23 LIDAR PROCESSING REPORT

2024

Project ID: 231143
Work Unit: 300449

Prepared for:

USGS
science for a changing world

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NV5 GEOSPATIAL

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1. Summary / Scope

1.1. Summary

This report contains a summary of the CA San Francisco B23, Work Unit 300449 lidar acquisition task order, issued by USGS under their Contract 140G0223F0099 on March 22, 2023. The task order yielded a work unit area covering approximately 53 square miles over San Francisco, California at Quality Level 0. The intent of this document is only to provide specific validation information for the data acquisition/collection, processing, and production of deliverables completed as specified in the task order.

1.2. Scope

Aerial topographic lidar was acquired using state of the art technology along with the necessary surveyed ground control points (GCPs) and airborne GPS and inertial navigation systems. The aerial data collection was designed with the following specifications listed in Table 1 below.

Table 1. Originally Planned Lidar Specifications

Average Point Density	Flight Altitude (AGL)	Field of View	Minimum Side Overlap	RMSEz
50 pts / m2	1000 m	58.5°	55%	≤ 10 cm

1.3. Coverage

The work unit boundary covers approximately 53 square miles over San Francisco, California. Work unit extents are shown in Figure 1.

1.4. Duration

Lidar data was acquired from April 20, 2023 in one total lift. See “Section: 2.4. Time Period” for more details.

1.5. Issues

Tiles 05600195 and 05400315 are blank due to entirely being in the water and have no returns.

CA San Francisco B23 Work Unit 300449 Projected Coordinate System: San Francisco CS13 (EPSG 7131) Horizontal Datum: NAD83 (2011) Vertical Datum: NAVD88 (GEOID 18) Units: Meters	
Lidar Point Cloud	Classified Point Cloud in .LAS 1.4 format
Rasters	• 0.25-meter Hydro-flattened Bare Earth Digital Elevation Model (DEM) in GeoTIFF format • 0.25-meter Intensity images in GeoTIFF format • 0.25-meter Digital Surface Model (DSM) in GeoTIFF format • 0.5-meter Maximum Surface Height Raster • 0.5-meter Swath Seperation Images
Vectors	Shapefiles (*.shp) • Project Boundary • Lidar Tile Index • Flightlines Swath Geodatabase (*.gdb) • Continuous Hydro-flattened Breaklines
Reports	Reports in PDF format • Focus on Delivery • Focus on Accuracy • Survey Report • Processing Report
Metadata	XML Files (*.xml) • Breaklines • Classified Point Cloud • DEM • DSM • Intensity Imagery

CA San Francisco B23
Work Unit 300449 Boundary

Figure 1. Work Unit Boundary

2. Planning / Equipment

2.1. Flight Planning

Flight planning was based on the unique project requirements and characteristics of the project site. The basis of planning included: required accuracies, type of development, amount / type of vegetation within project area, required data posting, and potential altitude restrictions for flights in project vicinity.

Detailed project flight planning calculations were performed for the project using RiPARAMETER planning software.

2.2. Lidar Sensor

NV5 Geospatial utilized Riegl VQ1560ii lidar sensors (Figure 2), serial number(s) SN4890, for data acquisition.

The Riegl 1560ii system is a dual channel waveform processing airborne scanning system. It has a laser pulse repetition rate of up to 4 MHz resulting in up to 2.66 million measurements per second. The system utilizes a Multi-Pulse in the Air option (MPIA) and an integrated IMU/GNSS unit.

A brief summary of the aerial acquisition parameters for the project are shown in the lidar System Specifications in Table 2.

Table 2. Lidar System Specifications

		Riegl VQ1560ii (SN4890)
Terrain and Aircraft Scanner	Flying Height	1056 m
	Recommended Ground Speed	145 kts
Scanner	Field of View	58.5°
	Scan Rate Setting Used	2 x 256 lps
Laser	Laser Pulse Rate Used	2 x 2000 kHz
	Multi Pulse in Air Mode	Yes
Coverage	Full Swath Width	1183 m
	Line Spacing	0.283 m
Point Spacing and Density	Average Nominal Point Spacing	0.15 m
	Average Point Density	50 pts / m^2

Figure 2. Riegl VQ1560ii Lidar Sensor

2.3. Aircraft

All flights for the project were accomplished through the use of customized aircraft. Plane type and tail numbers are listed below.

Lidar Collection Planes
- Cessna Conquest 2 (twin-turboprop), Tail Number(s): N441CJ

These aircraft provided an ideal, stable aerial base for lidar acquisition. These aerial platforms have relatively fast cruise speeds, which are beneficial for project mobilization / demobilization while maintaining relatively slow stall speeds, proving ideal for collection of high-density, consistent data posting using a state-of-the-art lidar system. NV5 Geospatial's operating aircraft can be seen in Figure 3 below.

Figure 3. NV5 Geospatial's Aircraft

2.4. Time Period

Project specific flights were conducted on April 2, 2023. One aircraft lift were completed. Accomplished lifts are listed below.

Lift	Start UTC	End UTC
04202023A_4890_N441CJ	4/20/2023 11:07:40 am	4/20/2023 2:54:29 pm

3. Processing Summary

3.1. Flight Logs

Flight logs were completed by Lidar sensor technicians for each mission during acquisition. These logs depict a variety of information, including:

- Job / Project #
- Flight Date / Lift Number
- FOV (Field of View)
- Scan Rate (HZ)
- Pulse Rate Frequency (Hz)
- Ground Speed
- Altitude
- Base Station
- PDOP avoidance times
- Flight Line #
- Flight Line Start and Stop Times
- Flight Line Altitude (AMSL)
- Heading
- Speed
- Returns
- Crab

Notes: (Visibility, winds, ride, weather, temperature, dew point, pressure, etc). Project specific flight logs for each sortie are available in Appendix A.

3.2. Lidar Processing

Applanix + POSPac software was used for post-processing of airborne GPS and inertial data (IMU), which is critical to the positioning and orientation of the lidar sensor during all flights. Applanix POSPac combines aircraft raw trajectory data with stationary GPS base station data yielding a "Smoothed Best Estimate Trajectory" (SBET) necessary for additional post processing software to develop the resulting geo-referenced point cloud from the lidar missions.

During the sensor trajectory processing (combining GPS & IMU datasets) certain statistical graphs and tables are generated within the Applanix POSPac processing environment which are commonly used as indicators of processing stability and accuracy. This data for analysis include: max horizontal / vertical GPS variance, separation plot, altitude plot, PDOP plot, base station baseline length, processing mode, number of satellite vehicles, and mission trajectory.

Point clouds in flightline swath format were created using the RiPROCESS software. The generated point cloud is the mathematical three dimensional composite of all returns from all laser pulses as determined from the aerial mission. Each flightline swath point cloud was calibrated using Strip Align software that corrects systematic geometric errors and improves the relative and absolute accuracy of the flightline swath point cloud. The calibrated point cloud swaths were imported into GeoCue distributive processing software and the imported data was then tiled so further processing could take place in TerraScan software. Using TerraScan, the vertical accuracy of the surveyed ground control was tested and any vertical bias was removed from the data. TerraScan and TerraModeler software packages were then used for automated data classification and manual cleanup. The data were manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler.

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

Finally, proprietary software is used to perform statistical analysis of the LAS files.

Software	Version
Applanix + POSPac	8.6
RiPROCESS	1.8.6
Microstation Connect	10.16.02.34
GeoCue	2020.1.22.3
Global Mapper	19.1;20.1
TerraModeler	21.008
TerraScan	21.016
TerraMatch	21.007
StripAlign	2.21

3.3. LAS Classification Scheme

The classification classes are determined by Lidar Base Specifications 2023 Rev. A and are an industry standard for the classification of lidar point clouds. All data starts the process as Class 1 (Unclassified), and then through automated classification routines, the classifications are determined using TerraScan macro processing.

The classes used in the dataset are as follows and have the following descriptions:

Table 3. LAS Classifications

	Classification Name	Description
1	Processed, but Unclassified	Laser returns that are not included in the bare earth class, or any other project classification
2	Bare earth	Laser returns that are determined to be bare earth using automated and manual cleaning algorithms
7	Low Noise	Laser returns that are often associated with scattering from reflective surfaces, or artificial points below the bare earth surface
9	Water	Laser returns that are found inside of hydro features
17	Bridge Deck	Laser returns falling on bridge decks
18	High Noise	Laser returns that are often associated with birds or artificial points above the bare earth surface
20	Ignored Ground	Bare earth points that fall within the given threshold of a collected hydro feature.

3.4. Classified LAS Processing

The bare earth surface is then manually reviewed to ensure correct classification on the Class 2 (Ground) points. After the bare- earth surface is finalized; it is then used to generate all hydro-breaklines through heads-up digitization.

All ground (ASPRS Class 2) lidar data inside of the Lake Pond and Double Line Drain hydro flattening breaklines were then classified to water (ASPRS Class 9) using proprietary tools. A buffer of 1.5 feet/0.5 meter was also used around each hydro flattened feature to classify these ground (ASPRS Class 2) points to Ignored ground (ASPRS Class 20). All Lake Pond Island and Double Line Drain Island features were checked to ensure that the ground (ASPRS Class 2) points were reclassified to the correct classification after the automated classification was completed.

Any noise that was identified either through manual review or automated routines was classified to the appropriate class (ASPRS Class 7 and/or ASPRS Class 18) followed by flagging with the withheld bit.

All data was manually reviewed and any remaining artifacts removed using functionality provided by TerraScan and TerraModeler. Global Mapper is used as a final check of the bare earth dataset. GeoCue was then used to create the deliverable industry-standard LAS files for all point cloud data. NV5 Geospatial's proprietary software was used to perform final statistical analysis of the classes in the LAS files, on a per tile level to verify final classification metrics and full LAS header information.

3.5. Hydro-Flattened Breakline Processing

Using heads-up digitization, all Lake-Ponds, Double Line Drains, and Islands are manually collected that are within the project size specification. This includes Lake-Ponds greater than 2 acres in size, Double Line Drains with greater than a 100 foot nominal width, and Islands greater than 1 acre in size within a collected hydro feature. Lidar intensity imagery and bare-earth surface models are used to ensure appropriate and complete collection of these features.

Elevation values are assigned to all collected hydro features via NV5 Geospatial's proprietary software. This software sets Lake-Ponds to an appropriate, single elevation to allow for the generation of hydro-flattened digital elevation models (DEM). Double Line Drain elevations are assigned based on lidar elevations and surrounding terrain feature to ensure all breaklines match the lidar within acceptable tolerances. Some deviation is expected between breakline and lidar elevations due to monotonicity, connectivity, and flattening rules that are enforced on the breaklines. Once complete, horizontal placement, and vertical variances are reviewed, all breaklines are evaluated for topological consistency and data integrity using a combination of proprietary tools and manual review of hydro-flattened DEMs.

Breaklines are combined into one seamless shapefile, clipped to the project boundary, and imported into an Esri file geodatabase for delivery.

3.6. Hydro-Flattened Raster DEM Processing

Hydro-Flattened DEMs (topographic) represent a lidar-derived product illustrating the grounded terrain and associated breaklines (as described above) in raster form. NV5 Geospatial's proprietary software was used to take all input sources (bare earth lidar points, bridge and hydro breaklines, etc.) and create a Triangulated Irregular Network (TIN) on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper triangulation can occur. From the TIN, linear interpolation is used to calculate the cell values for the raster product. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF DEM was generated for each tile with a pixel size of 0.25-meter. NV5 Geospatial's proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each DEM is reviewed in Global Mapper to check for any surface anomalies and to ensure a seamless dataset. NV5 Geospatial ensures there are no void or no-data values (-999999) in each derived DEM. This is achieved by using propriety software checking all cell values that fall within the project boundary. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

3.7. Intensity Image Processing

Intensity images represent reflectivity values collected by the lidar sensor during acquisition. Proprietary software generates intensity images using first returns and excluding those flagged with a withheld bit. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written during product generation.

3.8. Swath Separation Raster Processing

Swath Separation Images are rasters that represent the interswath alignment between flight lines and provide a qualitative evaluation of the positional quality of the point cloud. NV5 Geospatial proprietary software generated 0.5-meter raster images in GeoTIFF format using last returns, excluding points flagged with the withheld bit, and using a point-in-cell algorithm. Images are generated with a 75% intensity opacity and (4) absolute 8-cm intervals, see below for interval coloring. Intensity images are linearly scaled to a value range specific to the project area to standardize the images and reduce differences between individual tiles. Appropriate horizontal projection information as well as applicable header values are written to the file during product generation. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the images against what is required before final delivery.

(green)	0-8cm
(yellow)	8-16cm
(orange)	16-24cm
(red)	>24cm

3.9. Maximum Surface Height Raster Processing

Maximum Surface Height rasters (topographic) represent a lidar-derived product illustrating natural and built-up features. NV5 Geospatial's proprietary software was used to take all classified lidar points, excluding those flagged with a withheld bit, and create a raster on a tile-by-tile basis. Data extending past the tile edge is incorporated in this process so that proper gridding can occur. The raster is created by laying a 0.5-meter DEM cell size over the area and assigning the values to cells by using the maximum lidar point that intersects that grid cell. The raster product is then clipped back to the tile edge so that no overlapping cells remain across the project area. A 32-bit floating point GeoTIFF was then generated for each tile with a pixel size of 0.5-meter. There is no interpolation type being used in creating the raster product. NV5 Geospatial's proprietary software was used to write appropriate horizontal and vertical projection information as well as applicable header values into the file during product generation. Each maximum surface height raster is reviewed in Global Mapper to check for any anomalies and to ensure a seamless dataset. NV5 Geospatial uses a proprietary tool called FOCUS on Delivery to check all formatting requirements of the DEMs against what is required before final delivery.

3.10. Point Density

The acquisition parameters were designed to acquire an average first-return density of 50 points/m2. First return density describes the density of pulses emitted from the laser that return at least one echo to the system. Multiple returns greater than 1 from a single pulse were not considered in first return density analysis. Some types of surfaces (e.g., breaks in terrain, water, and steep slopes) may have returned fewer pulses than originally emitted by the laser. First returns typically reflect off the highest feature on the landscape within the footprint of the pulse. In forested or urban areas, the highest feature could be a tree, building or power line, while in areas of unobstructed ground, the first return will be the only echo and represents the bare earth surface.

The density of ground-classified lidar returns was also analyzed for this project. Terrain character, land cover, and ground surface reflectivity all influenced the density of ground surface returns. In vegetated areas, fewer pulses may penetrate the canopy, resulting in lower ground density.

The average first-return density of lidar data for the project was 90.1 points/m2 while the average ground classified density was 40.8 points/m2. The statistical and spatial distributions of first return densities and classified ground return densities per 100 m x 100 m cell are portrayed in Figures 4 and 5.

CA San Francisco B23
Work Unit 300449 First Return Point Density

Figure 4. First Return Point Density

CA San Francisco B23
Work Unit 300449 Ground Point Density

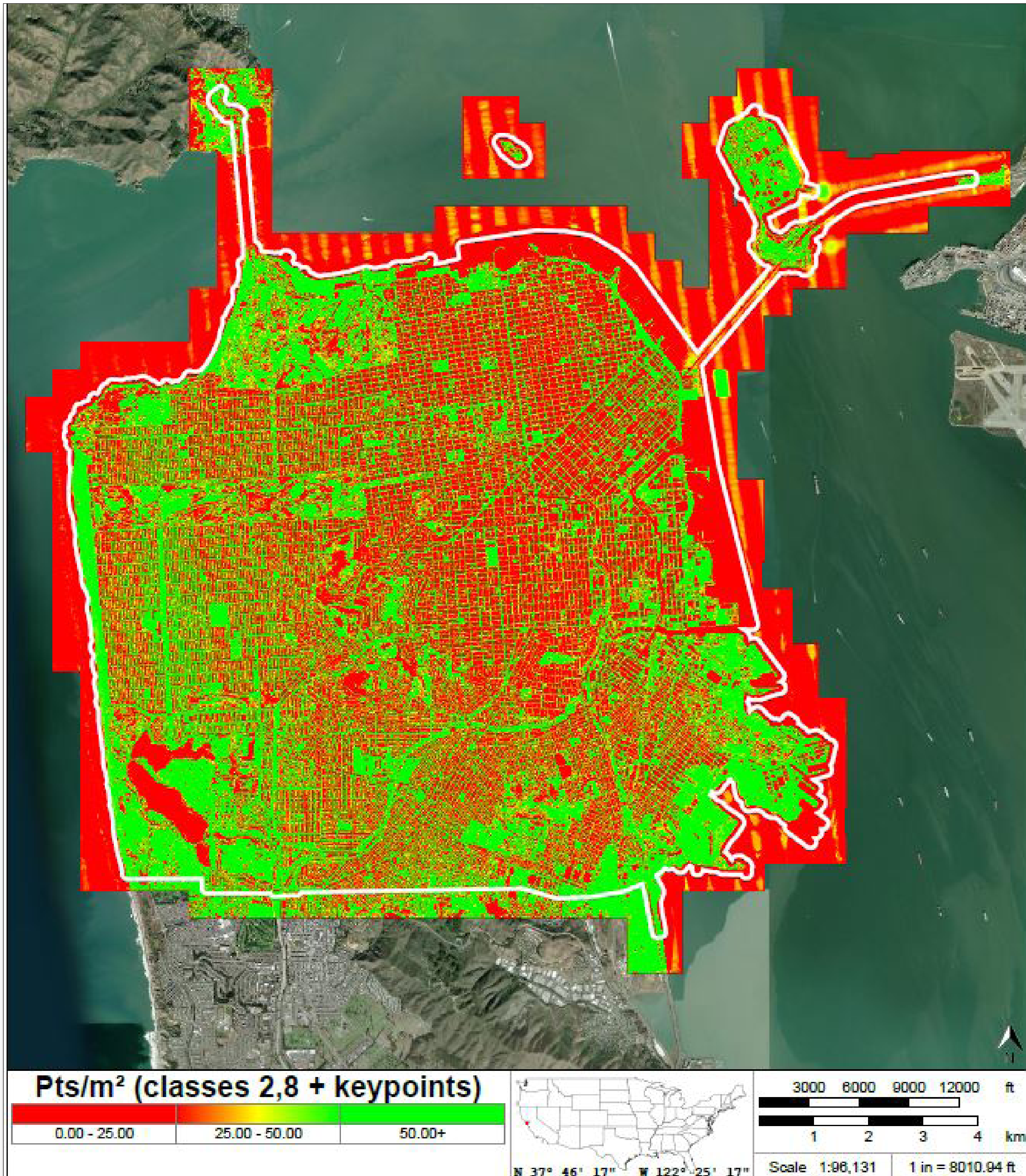


Figure 5. Ground First Return Point Density

CA San Francisco B23
Work Unit 300449 Tile Layout

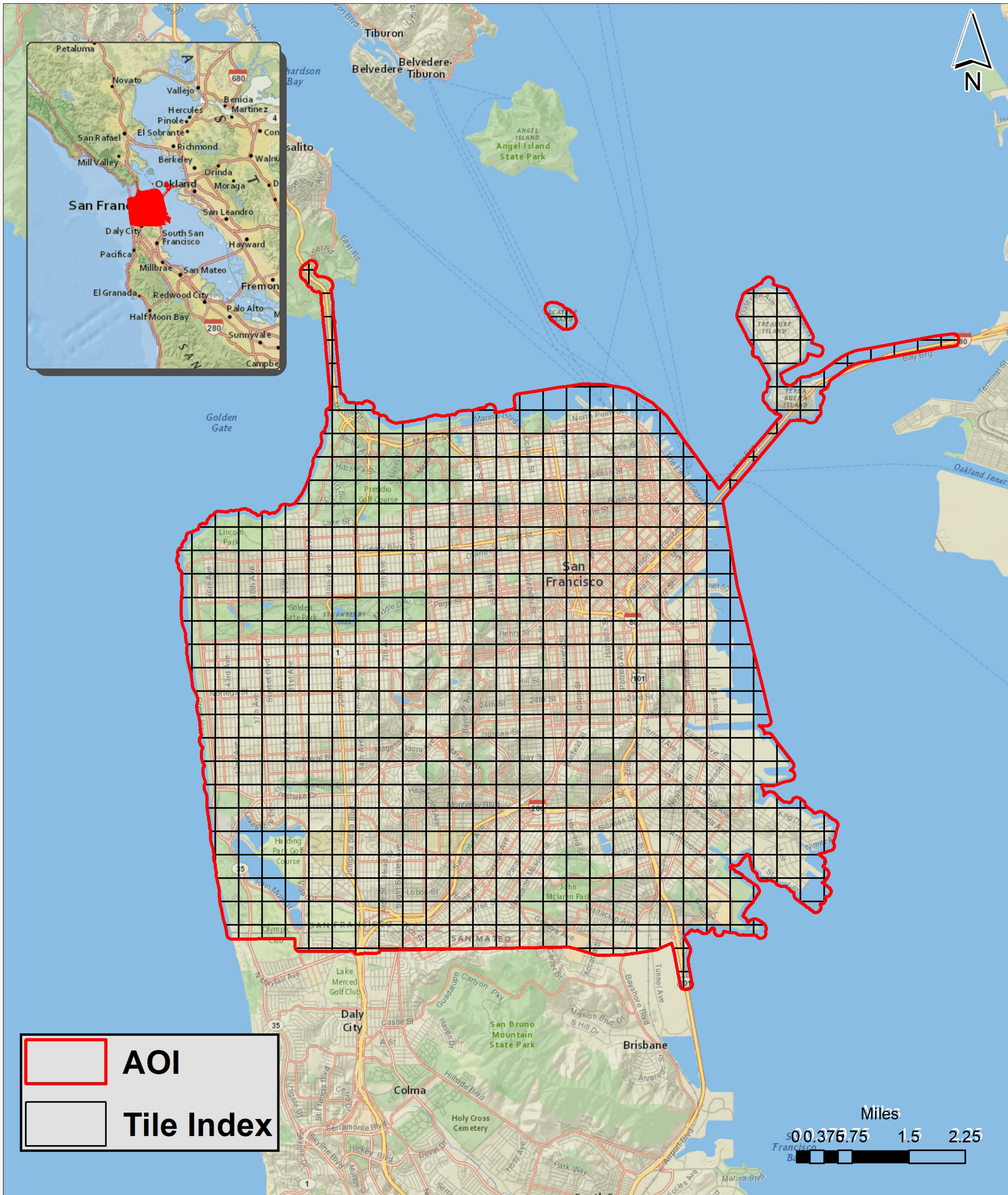


Figure 6. Lidar Tile Layout

4. Project Coverage Verification

A proprietary tool (FOCUS on Flight) produces grid-based polygons of each flightline, depicting exactly where lidar points exist. These swath polygons are reviewed against the project boundary to verify adequate project coverage. Please refer to Figure 7.

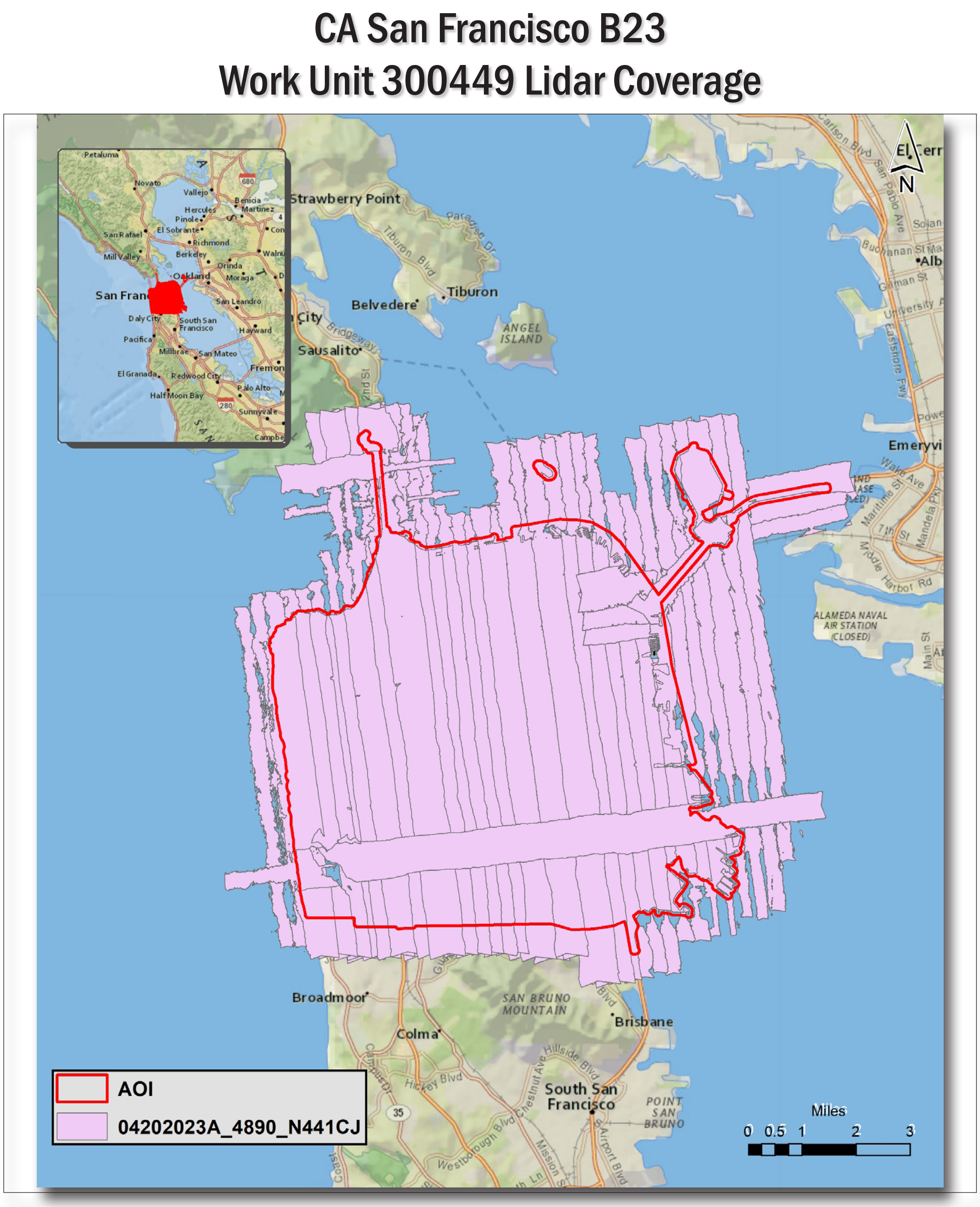


Figure 7. Lidar Coverage

5. Accuracy Testing

5.1. Calibration Control Point Testing

Figure 8 shows the location of each bare earth calibration point for the project area. TerraScan was used to perform a quality assurance check using the lidar bare earth calibration points. The results of the surface calibration are not an independent assessment of the accuracy of these project deliverables, but the statistical results do provide additional feedback as to the overall quality of the elevation surface.

5.2. Point Cloud Testing

The project specifications require that only Non-Vegetated Vertical Accuracy (NVA) be computed for raw lidar point cloud swath files. The required accuracy (ACCz) is: 19.6 cm at a 95% confidence level, derived according to NSSDA, i.e., based on RMSE of 10 cm in the “bare earth” and “urban” land cover classes. The NVA was tested with 30 checkpoints located in bare earth and urban (non-vegetated) areas. These check points were not used in the calibration or post processing of the lidar point cloud data. The checkpoints were distributed throughout the project area and were surveyed using GPS techniques. See survey report for additional survey methodologies.

Elevations from the unclassified lidar surface were measured for the x,y location of each check point. Elevations interpolated from the lidar surface were then compared to the elevation values of the surveyed control points. AccuracyZ has been tested to meet 19.6 cm or better Non-Vegetated Vertical Accuracy at 95% confidence level using RMSE(z) x 1.9600 as defined by the National Standards for Spatial Data Accuracy (NSSDA); assessed and reported using National Digital Elevation Program (NDEP)/ASPRS Guidelines.

5.3. Digital Elevation Model (DEM) Testing

The project specifications require the accuracy (ACCz) of the derived DEM be calculated and reported in two ways:

1. The required NVA is: 19.6 cm at a 95% confidence level, derived according to NSSDA, i.e., based on RMSE of 10 cm in the “bare earth” and “urban” land cover classes. This is a required accuracy. The NVA was tested with 30 checkpoints located in bare earth and urban (non-vegetated) areas. See Figure 9.
2. Vegetated Vertical Accuracy (VVA): VVA shall be reported for “brushlands/low trees” and “tall weeds/crops” land cover classes. The target VVA is: 29.4 cm at the 95th percentile, derived according to ASPRS Guidelines, Vertical Accuracy Reporting for lidar Data, i.e., based on the 95th percentile error in all vegetated land cover classes combined. This is a target accuracy. The VVA was tested with 11 checkpoints located in tall weeds/crops and brushlands/low trees (vegetated) areas. The checkpoints were distributed throughout the project area. See Figure 10.

AccuracyZ has been tested to meet 19.6 cm or better Non-Vegetated Vertical Accuracy at 95% confidence level using RMSE(z) x 1.9600 as defined by the National Standards for Spatial Data Accuracy (NSSDA); assessed and reported using National Digital Elevation Program (NDEP)/ASRPS Guidelines.

A brief summary of results are listed below.

Table 4. Accuracy Results

	Target	Measured	Point Count
Raw NVA	0.196 m	0.345 m	30
NVA	0.196 m	0.0318 m	30
VVA	0.294 m	0.1189 m	11

CA San Francisco B23
Calibration Points

Figure 8. Calibration Control Point Locations

CA San Francisco B23
NVA Points

Figure 9. QC Checkpoint Locations - NVA

CA San Francisco B23
VVA Points

Figure 10. QC Checkpoint Locations - VVA

6. Geometric Accuracy

6.1. Horizontal Accuracy

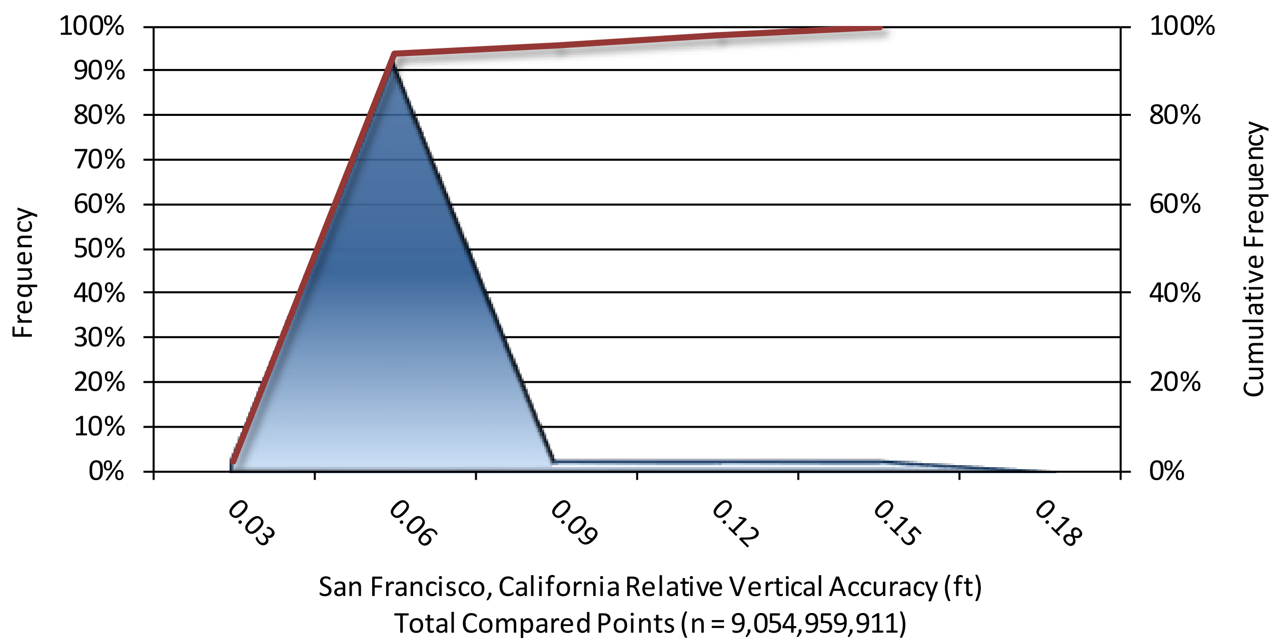
Lidar horizontal accuracy is a function of Global Navigation Satellite System (GNSS) derived positional error, flying altitude, and INS derived attitude error. The obtained $RMSE_r$ value is multiplied by a conversion factor of 1.7308 to yield the horizontal component of the National Standards for Spatial Data Accuracy (NSSDA) reporting standard where a theoretical point will fall within the obtained radius 95% of the time. Based on a flying altitude of 1056 meters, an IMU error of 0.002 decimal degrees, and a GNSS positional error of 0.015 meters, this project was compiled to meet 0.12 meter horizontal accuracy at the 95% confidence level. A summary is shown below.

Horizontal Accuracy	
$RMSE_r$	0.22 ft
	0.06 m
ACC_r	0.38 ft
	0.12 m

6.2. Relative Vertical Accuracy (Interswath Accuracy)

Relative vertical accuracy refers to the internal consistency of the data set as a whole: the ability to place an object in the same location given multiple flight lines, GPS conditions, and aircraft attitudes. When the lidar system is well calibrated, the swath-to-swath vertical divergence is low (<0.10 meters). The relative vertical accuracy was computed by comparing the ground surface model of each individual flight line with its neighbors in overlapping regions. The average (mean) line to line relative vertical accuracy for the CA San Francisco B23 project was 0.034 feet (0.010 meters). A summary is shown below.

Relative Vertical Accuracy	
Sample	47 flight line surfaces
Average	0.034 ft
	0.010 m
Median	0.034 ft
	0.011 m
RMSE	0.042 ft
	0.013 m
Standard Deviation (1σ)	0.017 ft
	0.005 m
1.96σ	0.033 ft
	0.010 m



6.3. Intraswath Precision (Smooth Surface Precision)

Intraswath Precision (smooth surface precision) is the measure of reliability of the lidar point cloud elevations along a planar surface. This measurement is performed on hard surfaces against a single flightline. NV5 digitized several large parking lots as polygons across the project area. These polygons were then used to calculate precision on a single FL basis using the below formula:

Precision = Range – (Slope x Cellsize x 1.414)

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

NV5 calculated the RMSDz to be 1.68 cm, minimum slope-corrected range to be 0 cm, and the maximum slope-corrected range to be 0.029 cm.

Project Report Appendices

The following section contains the appendices as listed in the CA San Francisco B23 Lidar Project Report.

Appendix A

Flight Logs

Project	946623-R040222.00	CA_SanFrancisco_B23
Flightplan	USGS_SanFran_QL0_50ppms_v2b	

		Mission Notes
Mission Name	S2224890_20230420_F1	
Mission Date	4/20/2023	Was able to finish the entire project in one lift.
Aircraft	N441CJ	
Pilot	Josey Billington	
Co-Pilot	Carl Christopher	
Operator	Logan Melgosa	
Co-Operator		
Vendor	NV5 Geospatial	
Base Airport	KOAK	
Departure (Local Time)	4:00:00 AM	
Arrival (Local Time)	8:22:00 AM	

Line	Heading	Start Time (UTC)	Stop Time (UTC)	Speed (kt)	Notes
00039	SW	11:07:35	11:08:24	151.5	
00038	E	11:11:10	11:11:57	163.1	
00037	SW	11:14:27	11:15:19	145.4	
00001	S	11:18:26	11:21:11	157.7	
00002	N	11:24:11	11:27:35	140.8	
00003	S	11:32:20	11:35:35	149.3	
00004	N	11:38:28	11:41:55	140.8	
00005	S	11:44:42	11:48:02	150.2	
00006	N	11:51:16	11:54:38	148.3	
00007	S	11:57:43	12:01:00	148.9	
00008	N	12:04:11	12:07:06	150.2	
00009	S	12:09:55	12:13:01	152.2	
00010	N	12:15:51	12:19:36	139.6	
00011	S	12:22:04	12:25:38	148.4	
00012	N	12:28:52	12:29:31	148.4	Aborted due to traffic, reflew
00012	N	12:32:17	12:35:45	153.5	Reflown line
00013	S	12:38:09	12:41:33	156.5	
00014	N	12:44:03	12:47:45	142.7	
00015	S	12:50:18	12:53:44	145.5	
00016	N	12:56:20	12:59:48	143.8	
00017	S	13:01:48	13:04:44	150.1	
00018	N	13:07:22	13:10:27	141.8	
00019	S	13:12:46	13:15:36	151.8	
00020	N	13:18:06	13:21:00	146.9	
00021	S	13:23:23	13:26:25	144.1	
00022	N	13:28:36	13:32:13	144.3	
00023	S	13:34:19	13:37:57	147.2	
00024	N	13:40:04	13:43:42	146.9	
00025	S	13:45:54	13:49:29	148.5	
00026	N	13:51:46	13:55:33	141.0	
00027	S	13:57:47	14:01:11	155.8	
00028	N	14:03:09	14:06:54	140.7	
00029	S	14:08:49	14:12:21	149.7	
00030	N	14:14:42	14:17:21	149.1	
00031	S	14:19:35	14:22:00	151.9	
00031	N	14:24:15	14:26:46	145.4	
00032	S	14:28:32	14:30:56	149.4	
00033	N	14:33:05	14:35:31	147.3	
00034	S	14:37:17	14:39:38	150.6	
00035	N	14:41:39	14:43:57	149.3	
00036	S	14:45:41	14:47:54	149.0	
00043	E	14:50:44	14:54:29	154.9	
00042	SW	14:56:55	14:57:26	146.8	
00041	E	14:59:15	14:59:45	155.0	
00040	SW	15:02:00	15:02:32	137.8	
00044	NE	15:04:19	15:05:12	137.7	
00046	SW	15:07:34	15:08:39	157.3	
00045	E	15:10:59	15:12:06	152.0	

Appendix B

SBET and POSPac Reports

General Information

Mission Information

Project name	04202023A_4890
Processing date	2023-05-03 01:45:17
Mission date	2023-04-20 10:43:16
Mission duration	04:42:52.000
Processing mode	IN-Fusion PP-RTX

Rover Hardware Information

Product	POS AV 610 VER6 HW2.5-12
Serial number	S/N11651
IMU type	57
Receiver type	BD982
Antenna type	AV59

Project File List

Rover Data Files

File name	File type
20230420A.603	POS Data
20230420A.604	POS Data
20230420A.605	POS Data
20230420A.606	POS Data
20230420A.607	POS Data
20230420A.608	POS Data
20230420A.609	POS Data
20230420A.610	POS Data
20230420A.611	POS Data
20230420A.612	POS Data
20230420A.613	POS Data
20230420A.614	POS Data
20230420A.615	POS Data
20230420A.616	POS Data
20230420A.617	POS Data
20230420A.618	POS Data
20230420A.619	POS Data
20230420A.620	POS Data
20230420A.621	POS Data
20230420A.622	POS Data
20230420A.623	POS Data
20230420A.624	POS Data
20230420A.625	POS Data
20230420A.626	POS Data
20230420A.627	POS Data
20230420A.628	POS Data
20230420A.629	POS Data
20230420A.630	POS Data
20230420A.631	POS Data
20230420A.632	POS Data
20230420A.633	POS Data
20230420A.634	POS Data
20230420A.635	POS Data
20230420A.636	POS Data
20230420A.637	POS Data
20230420A.638	POS Data
20230420A.639	POS Data
20230420A.640	POS Data
20230420A.641	POS Data
20230420A.642	POS Data
20230420A.643	POS Data
20230420A.644	POS Data
20230420A.645	POS Data
20230420A.646	POS Data
20230420A.647	POS Data
20230420A.648	POS Data
20230420A.649	POS Data
20230420A.650	POS Data
20230420A.651	POS Data
20230420A.652	POS Data
20230420A.653	POS Data

Input Files

File Name	File Type
Ephm1100.23g	GLONASS Broadcast Ephemeris
Ephm1100.23n	GPS Broadcast Ephemeris

Output Files

Filename	File type
sbet_04202023A_4890.out	SBET Trajectory File

Rover Data Summary

First raw data file	20230420A.603		
Last raw data file	20230420A.653		
Start GPS week	2258		
Start time	384177.633 (4/20/2023 10:42:57 AM)		
End time	401149.775 (4/20/2023 3:25:49 PM)		
Start of fine alignment	384215.490 (4/20/2023 10:43:35 AM)		
Available subsystems	Primary GNSS, IMU		
POS Event Input	Event 1 Input, Event 2 Input, Event 3 Input		
Correction data	None		
IMU Installation Lever Arms & Mounting Angles			
Reference to IMU lever arm (m)	0.000	0.000	0.000
Reference to IMU mounting angles (deg)	0.000	0.000	0.000
Reference to Primary GNSS lever arm (m)	1.181	-0.237	-0.994
Reference to Primary GNSS lever arm std dev (m)	-1.000		
Aircraft to Reference mounting angles (deg)	0.000	0.000	0.000

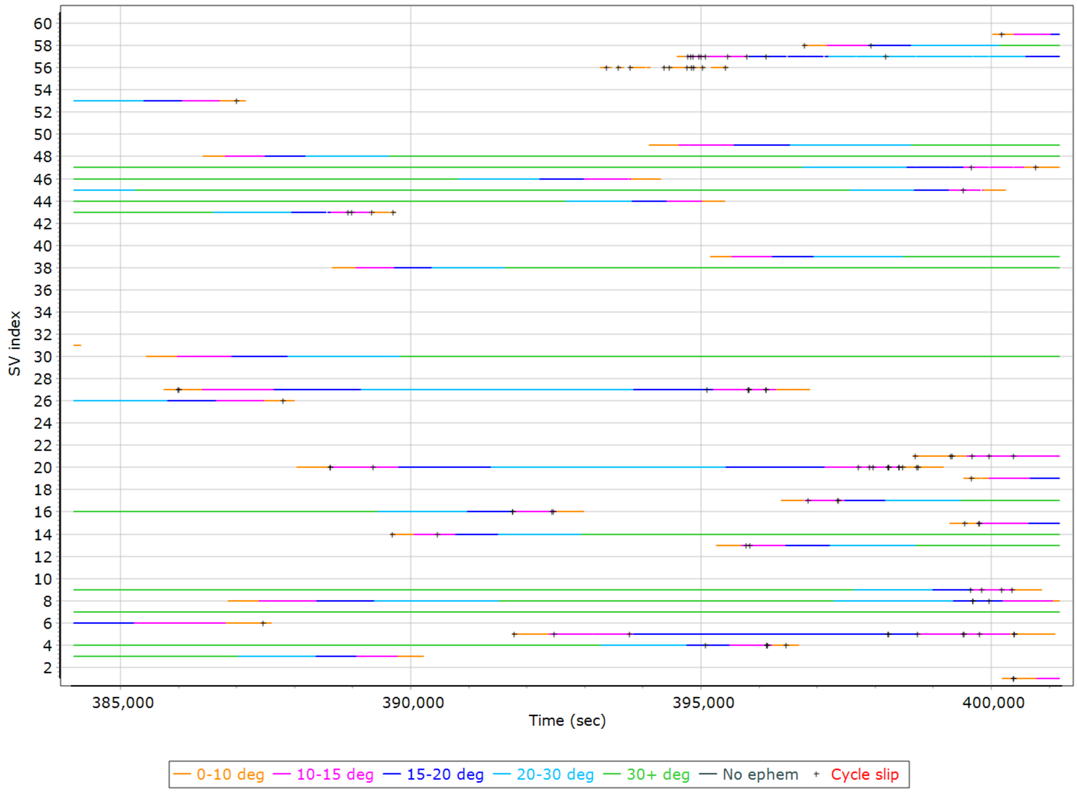
Rover Data QC

Raw IMU Import QC Summary

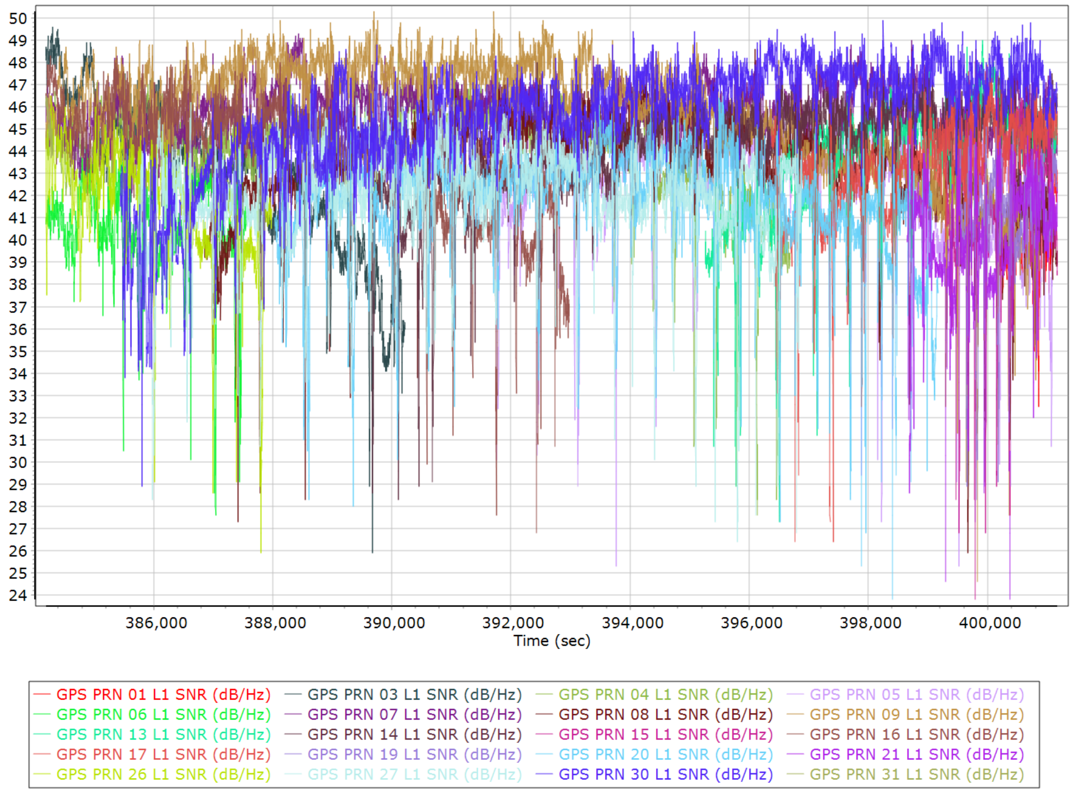
IMU data input file	imu_Mission 1.dat
IMU data check log file	imudt_04202023A_4890.log
IMU Records Processed	3393922
Termination Status	Normal
IMU Anomalies	0

Primary Observables & Satellite Data

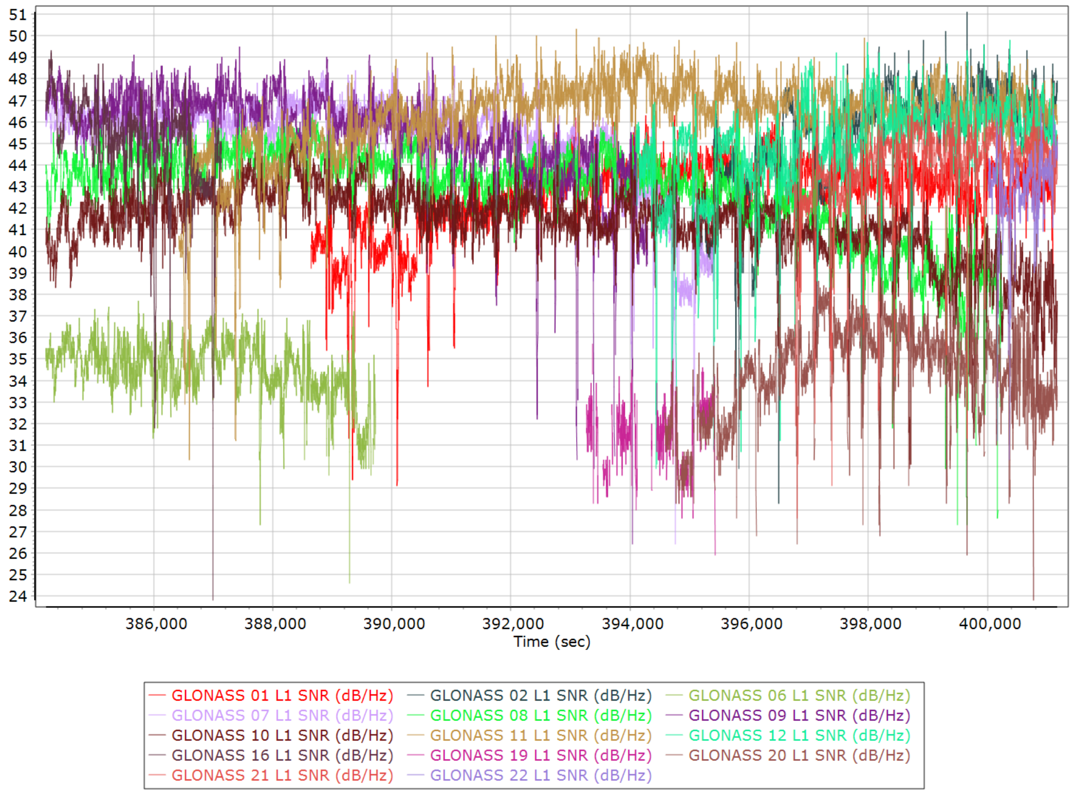
GPS/GLONASS L1 Satellite Lock/Elevation



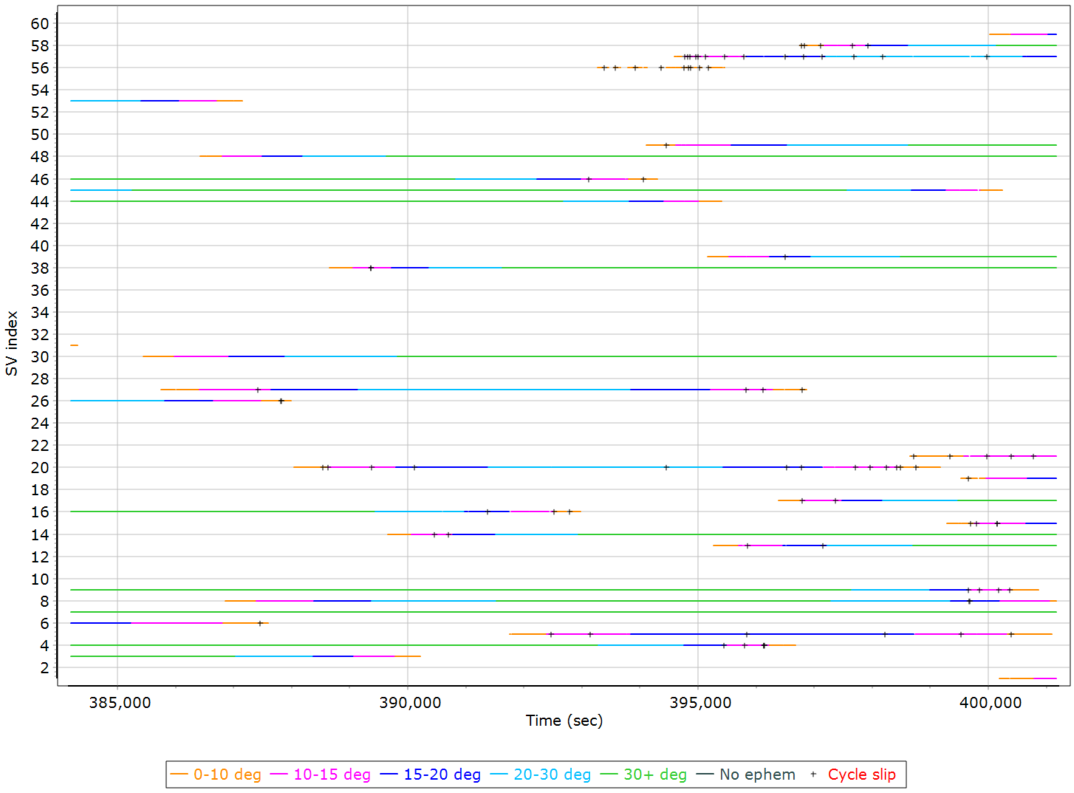
GPS L1 SNR



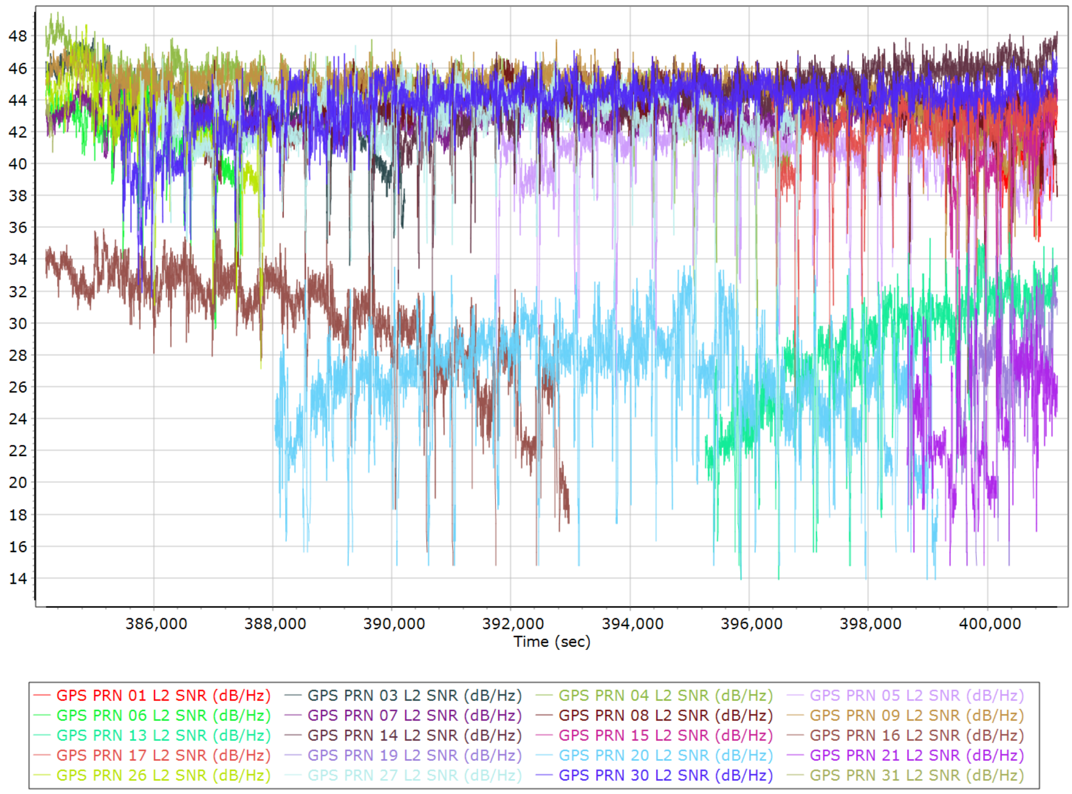
GLONASS L1 SNR



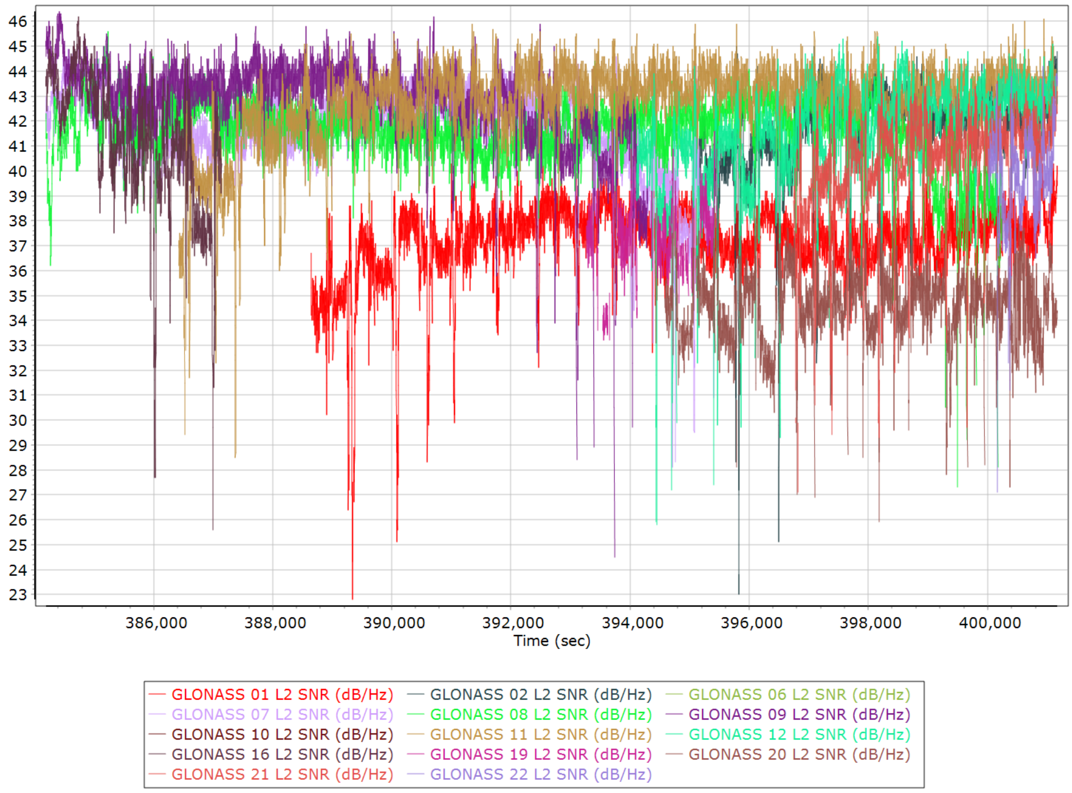
GPS/GLONASS L2 Satellite Lock/Elevation



GPS L2 SNR

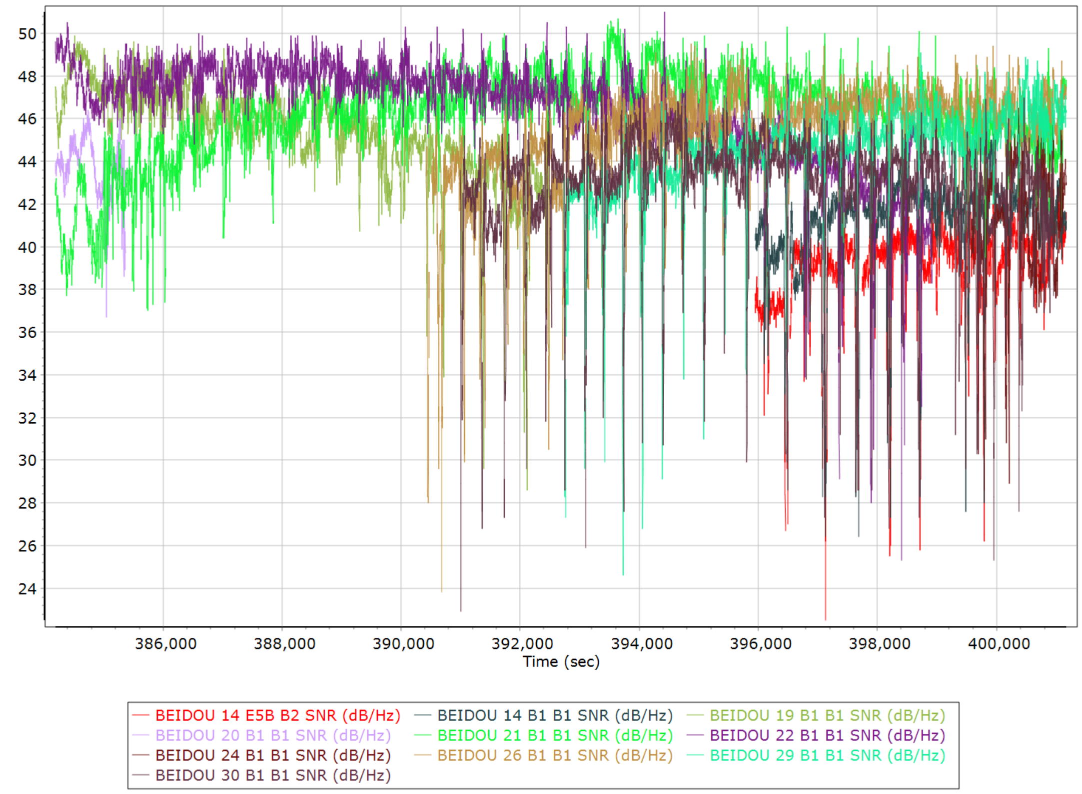


GLONASS L2 SNR

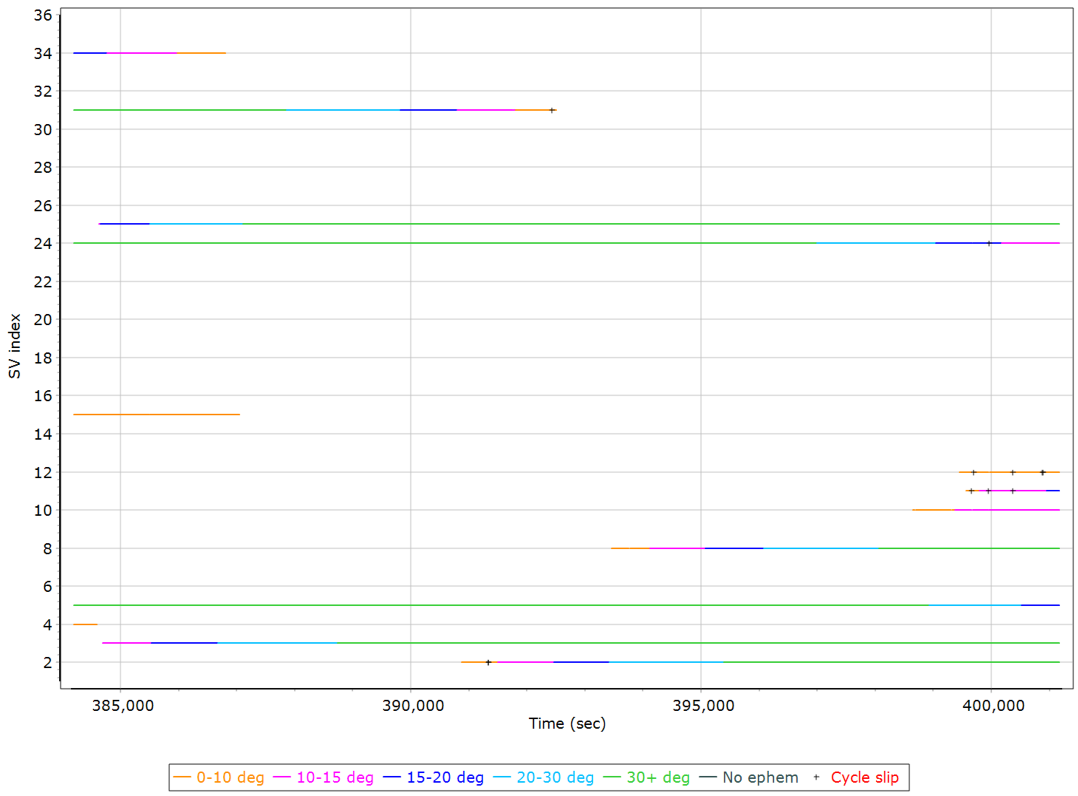


BEIDOU Satellite Lock/Elevation

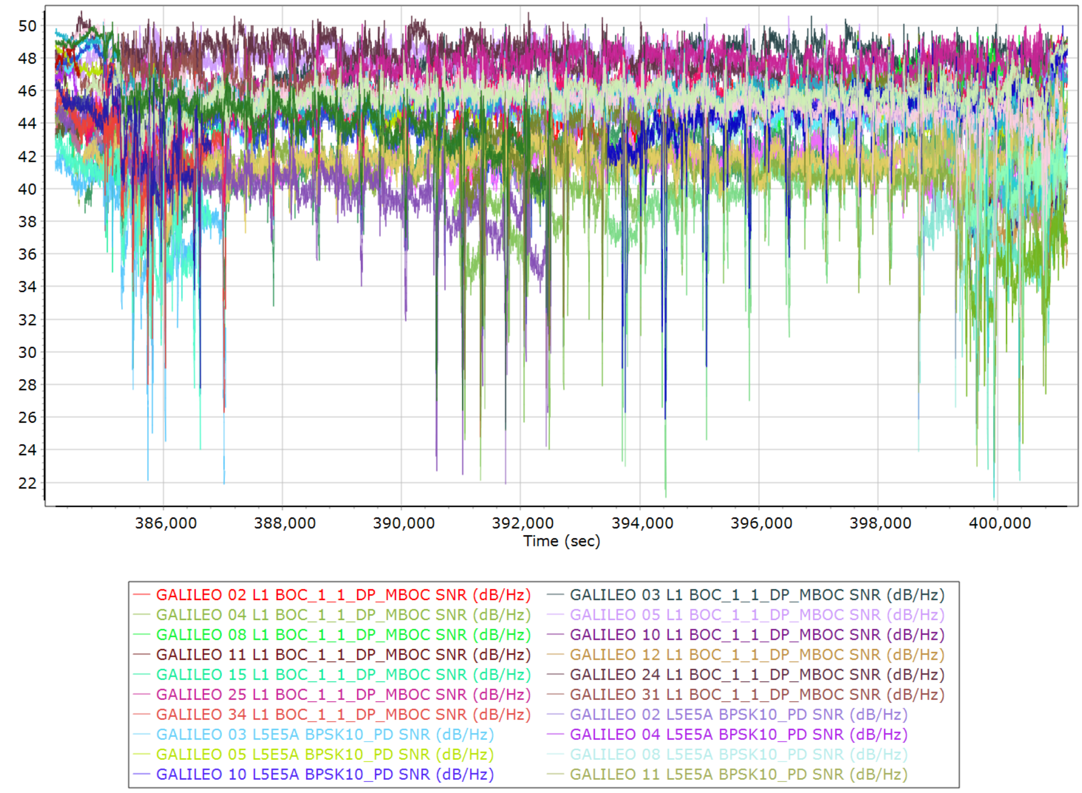
BEIDOU SNR



GALILEO Satellite Lock/Elevation

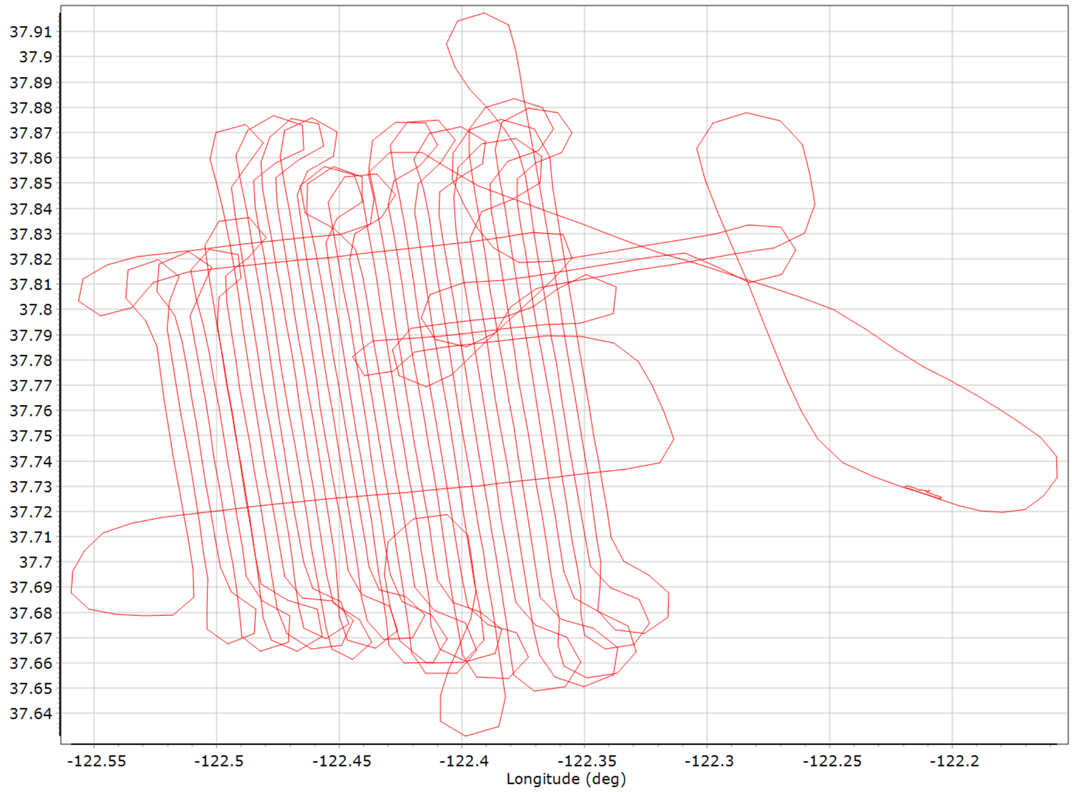


GALILEO SNR

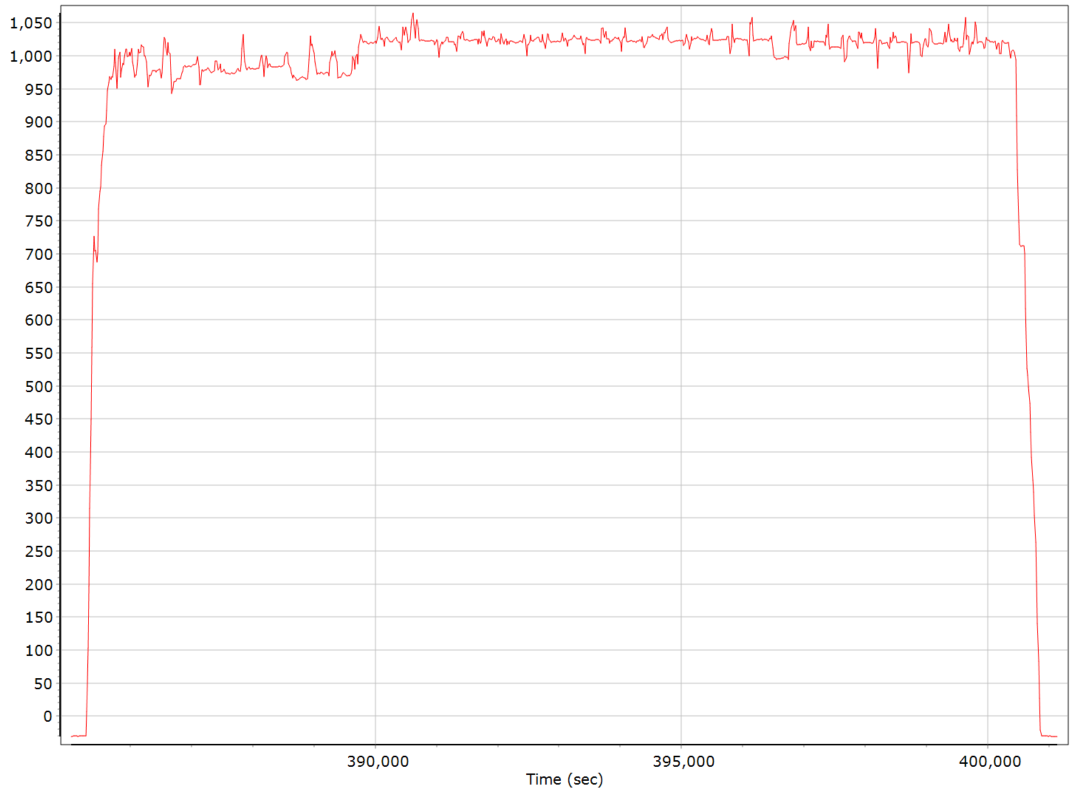

50
48
46
44
42
40
38
36
34
32
30
28
26
24
22
386,000
388,000
390,000
392,000
394,000
396,000
398,000
400,000
Time (sec)
GALILEO 02 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 03 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 04 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 05 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 08 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 10 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 11 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 12 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 15 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 24 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 25 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 31 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 34 L1 BOC_1_1_DP_MBOC SNR (dB/Hz)
GALILEO 02 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 03 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 04 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 05 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 08 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 10 L5E5A BPSK10_PD SNR (dB/Hz)
GALILEO 11 L5E5A BPSK10_PD SNR (dB/Hz)

Smoothed Trajectory Information

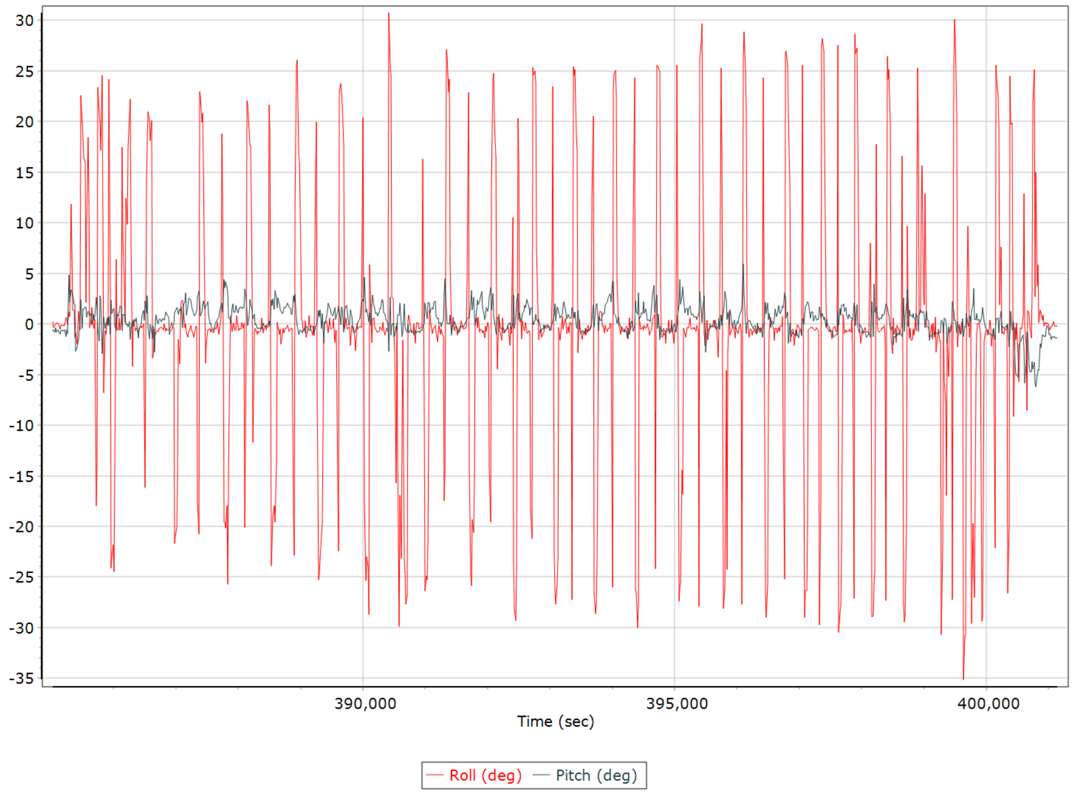
Top View



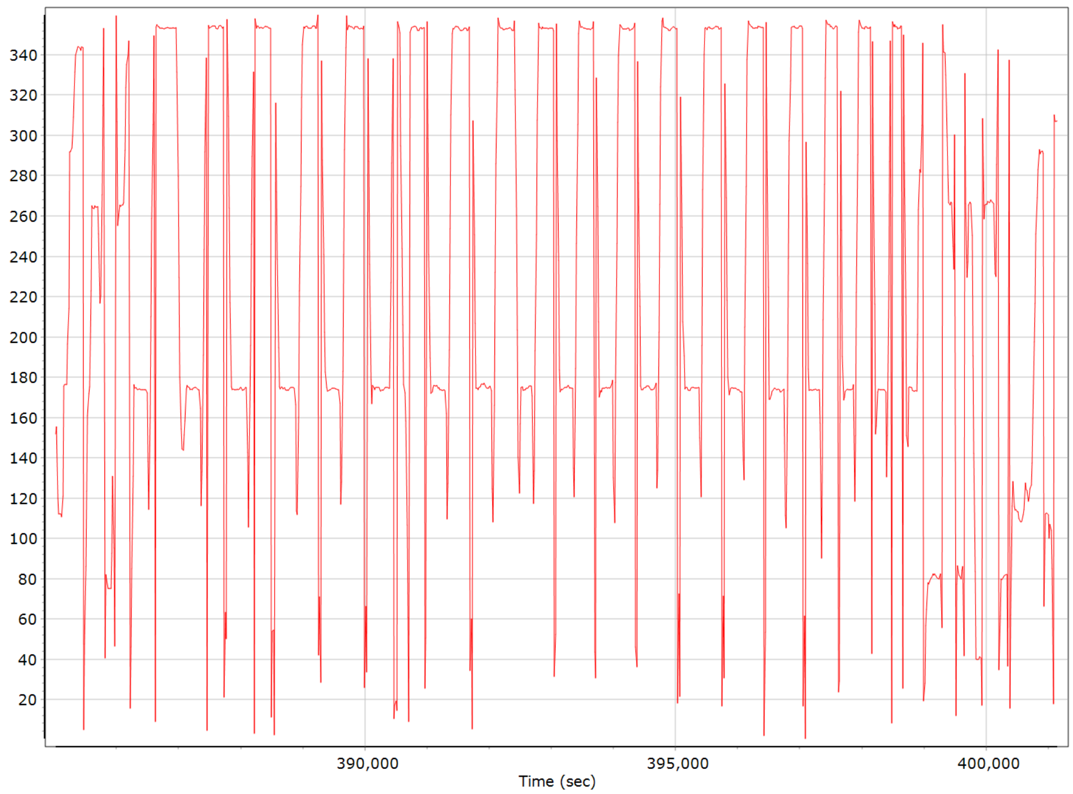
Altitude



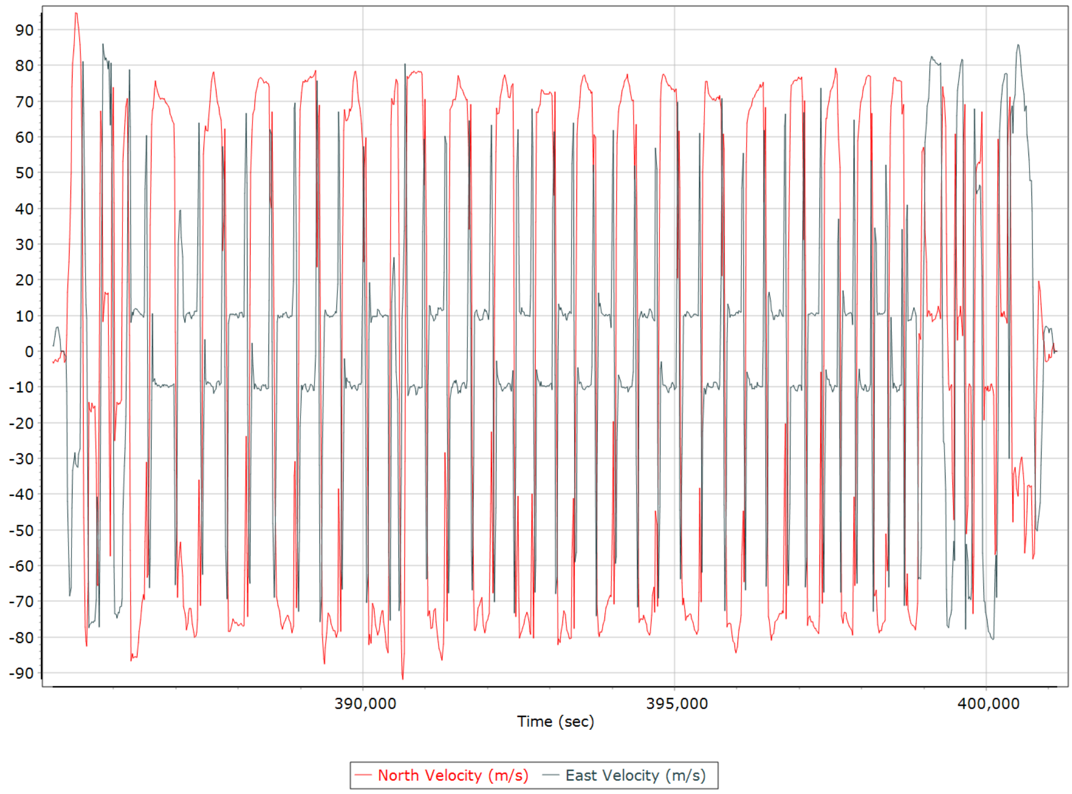
Roll/Pitch



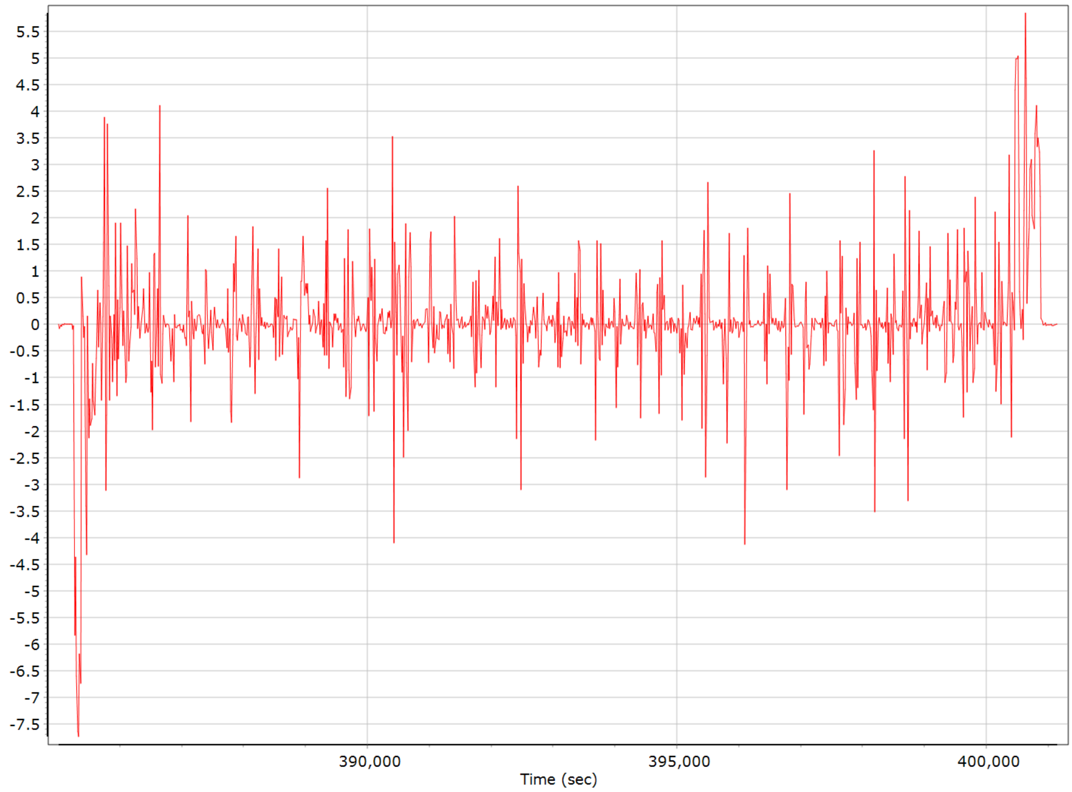
Heading



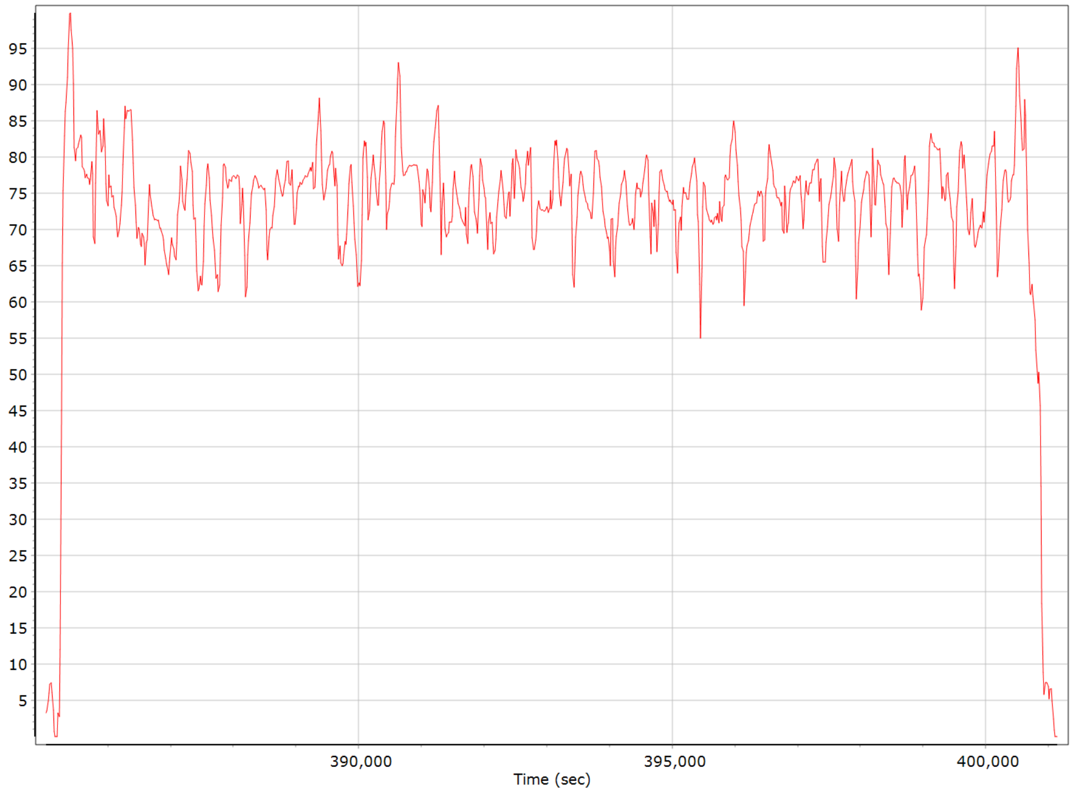
North/East Velocity



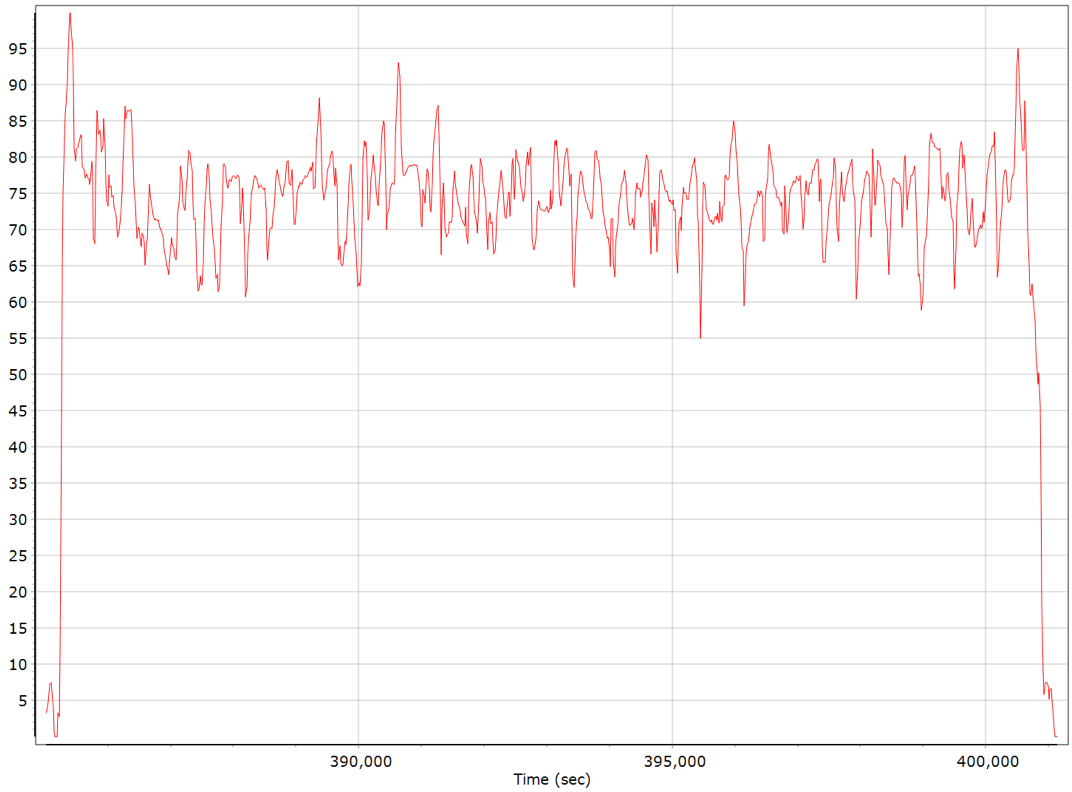
Down Velocity



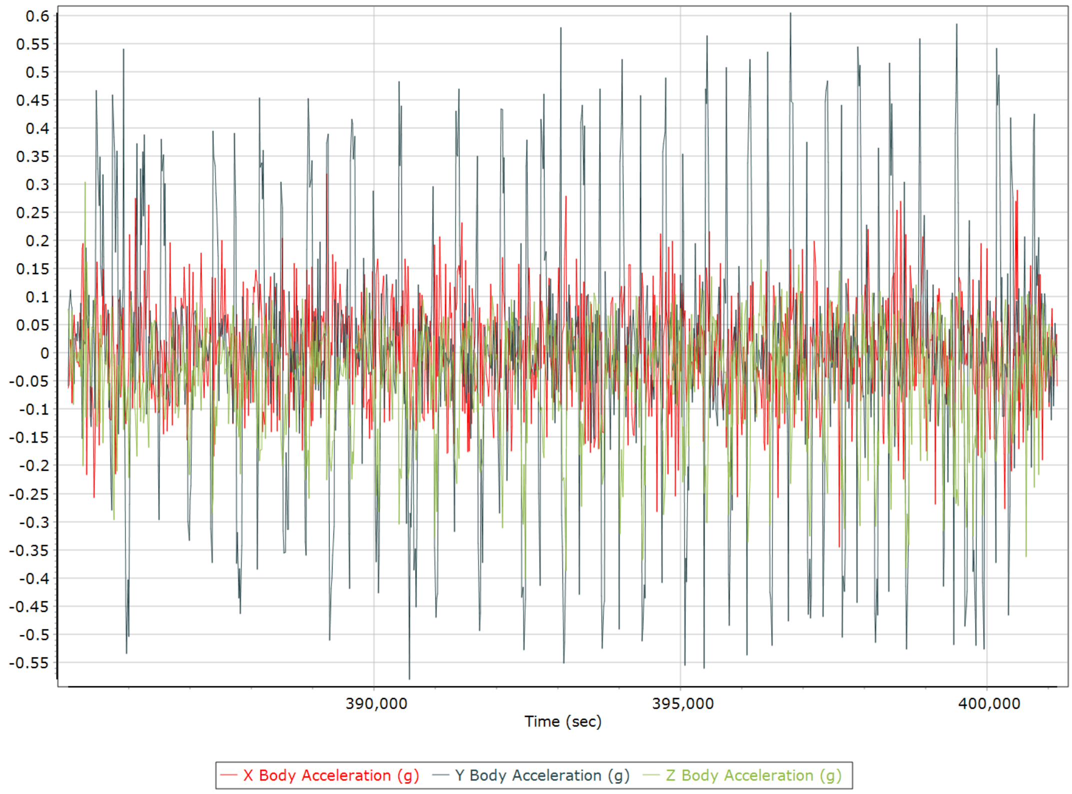
Total Speed



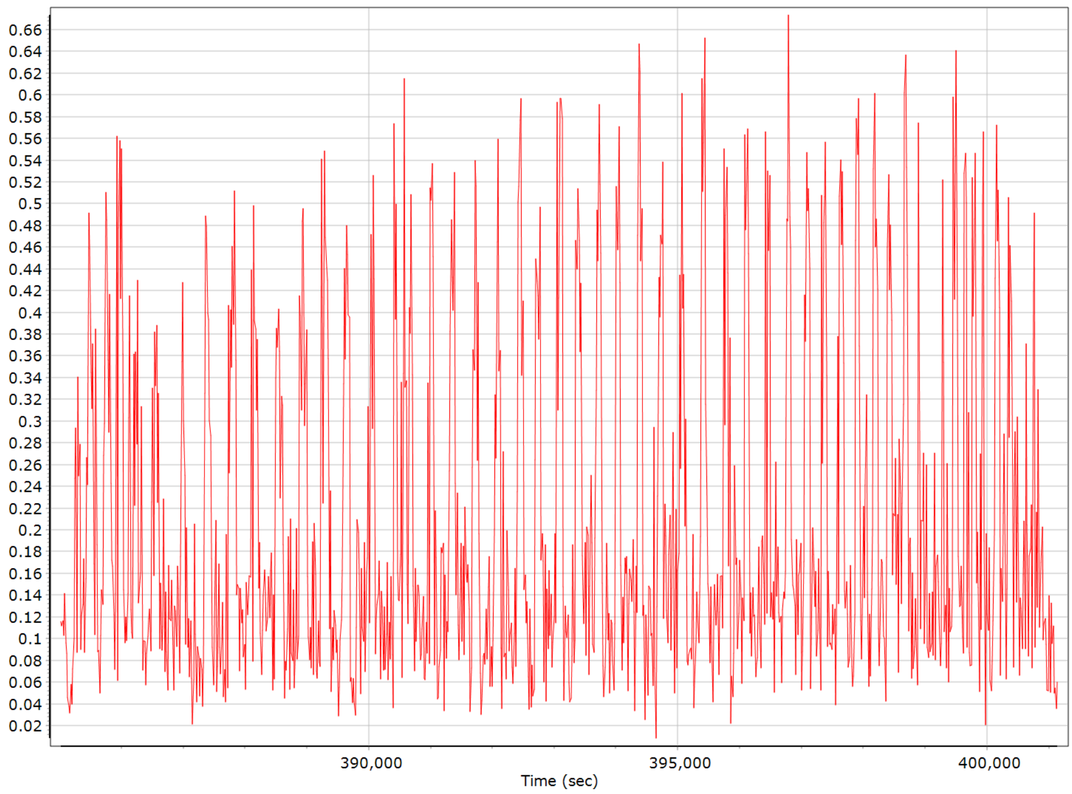
Ground Speed



Body Acceleration



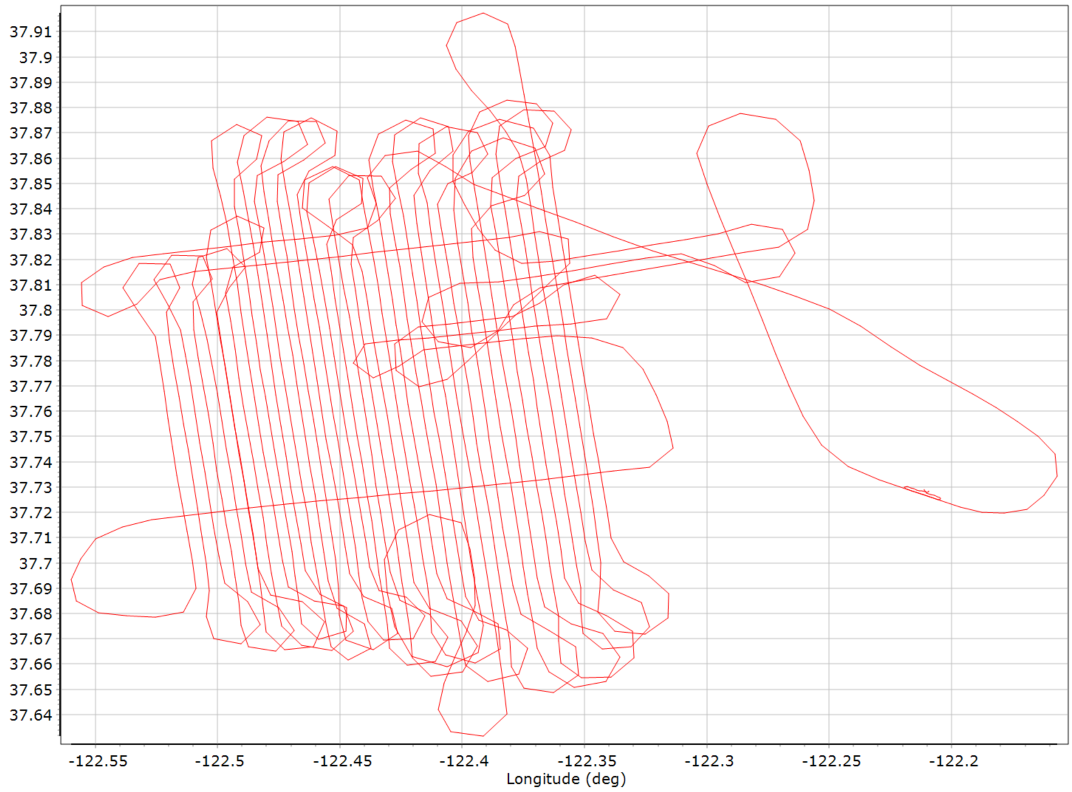
Total Body Acceleration



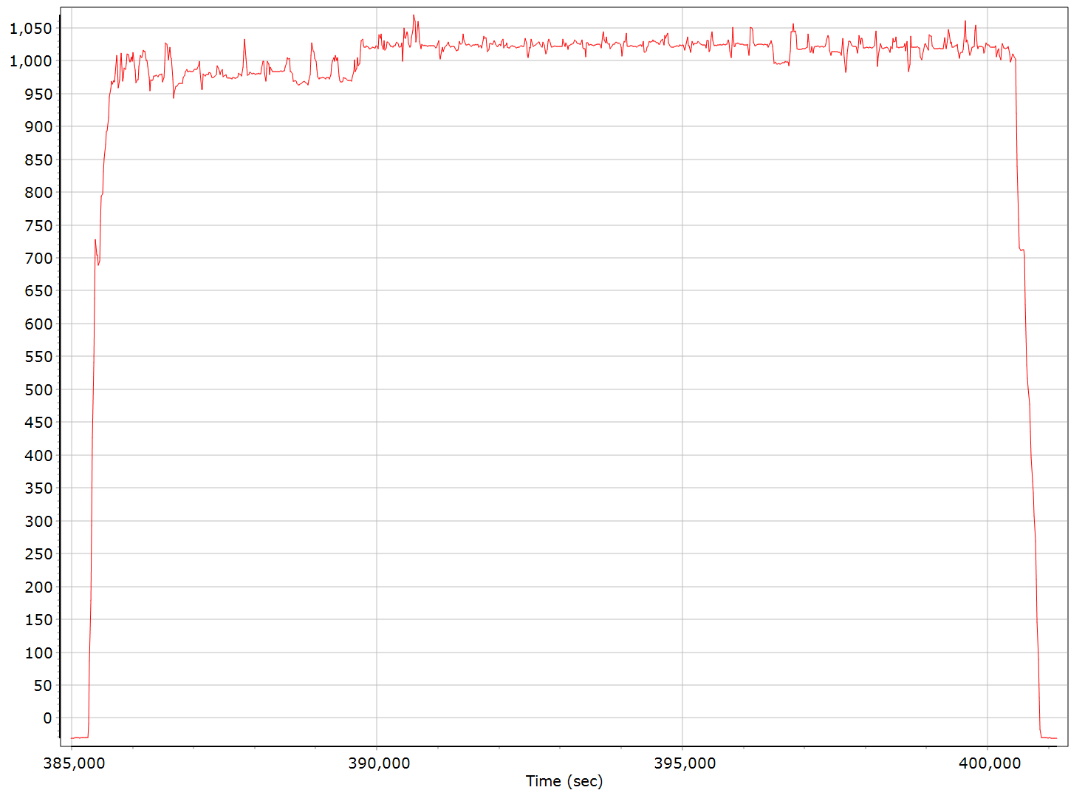
Body Angular Rate

Forward Processed Trajectory Information

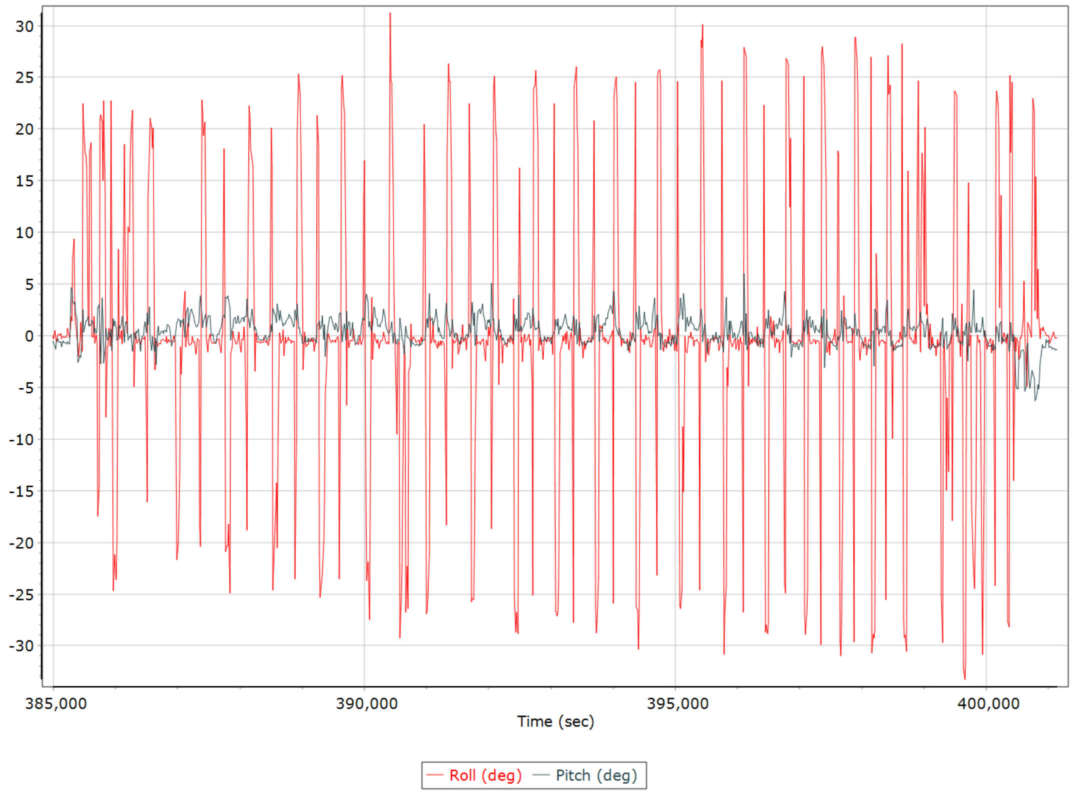
Top View



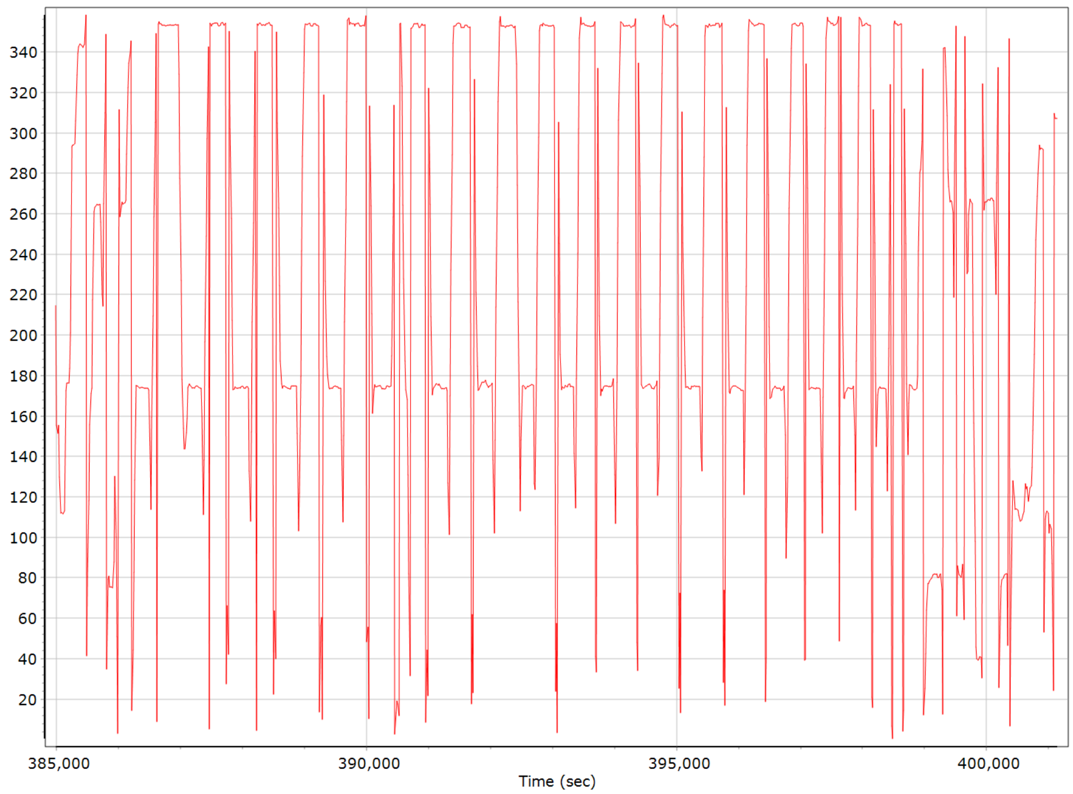
Altitude



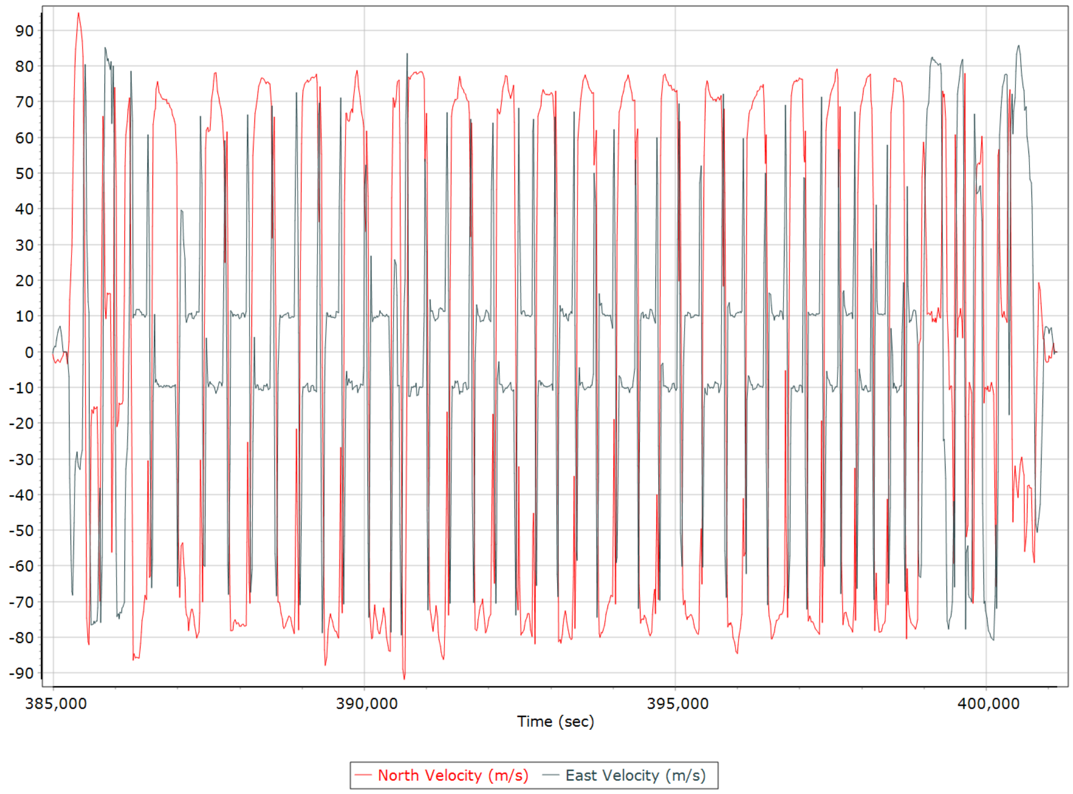
Roll/Pitch



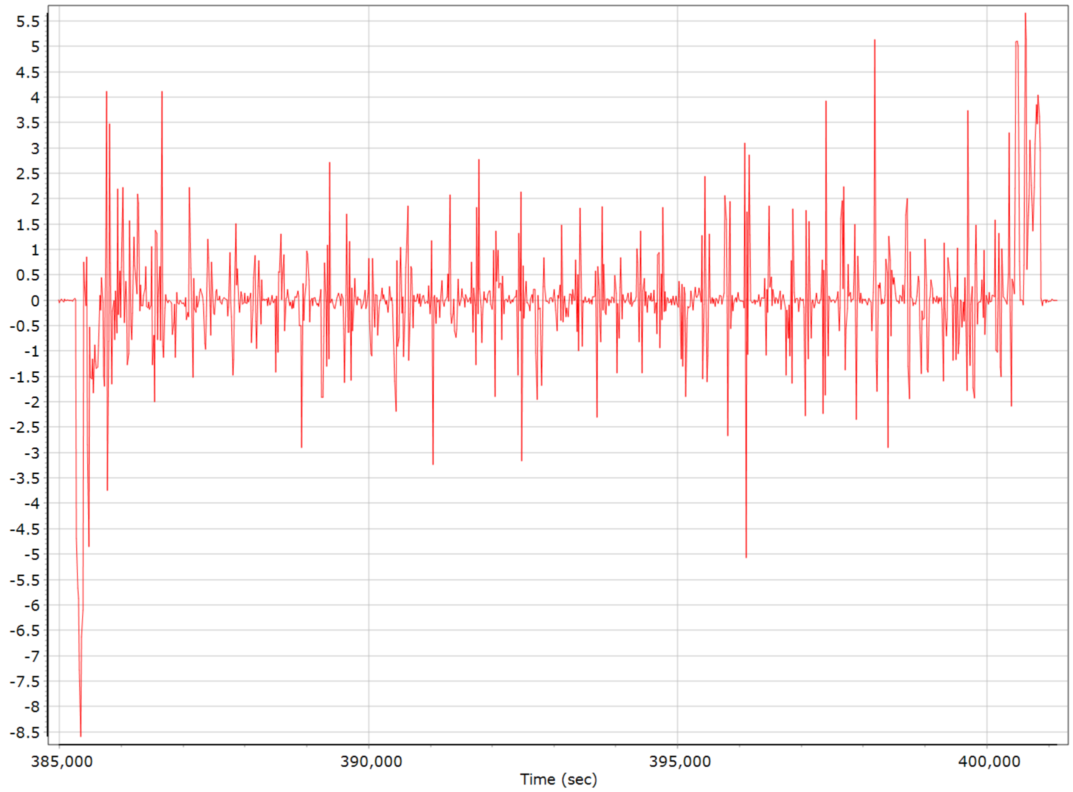
Heading



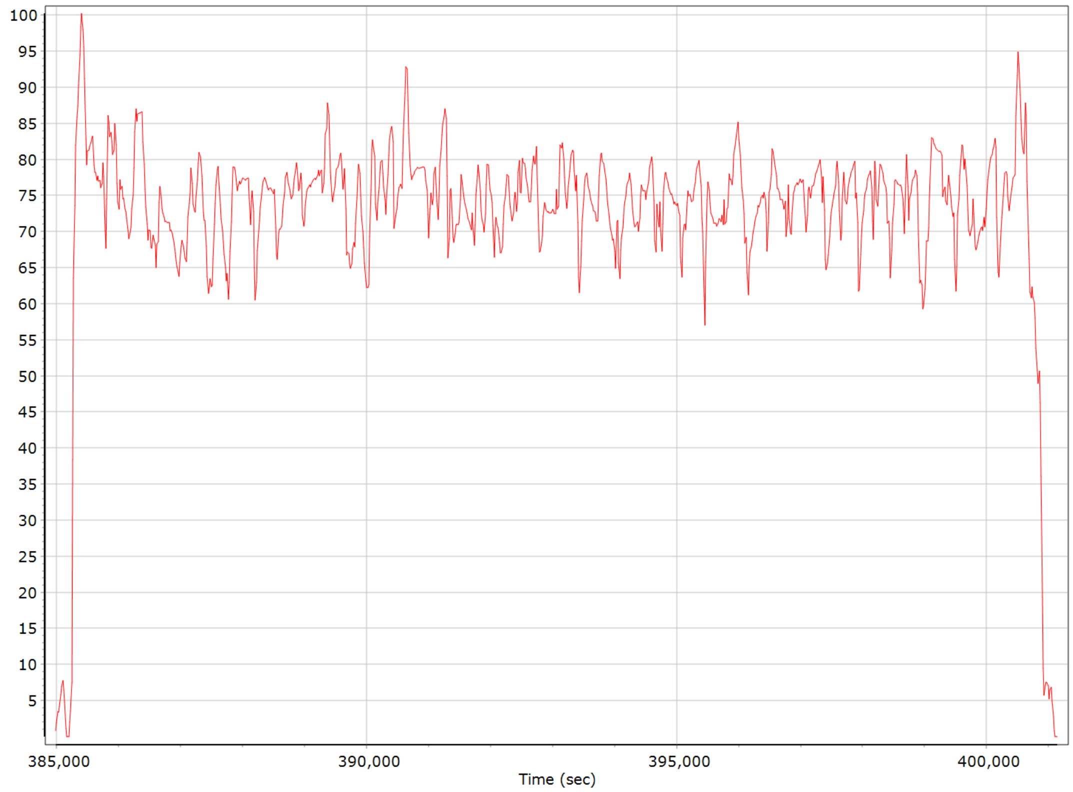
North/East Velocity



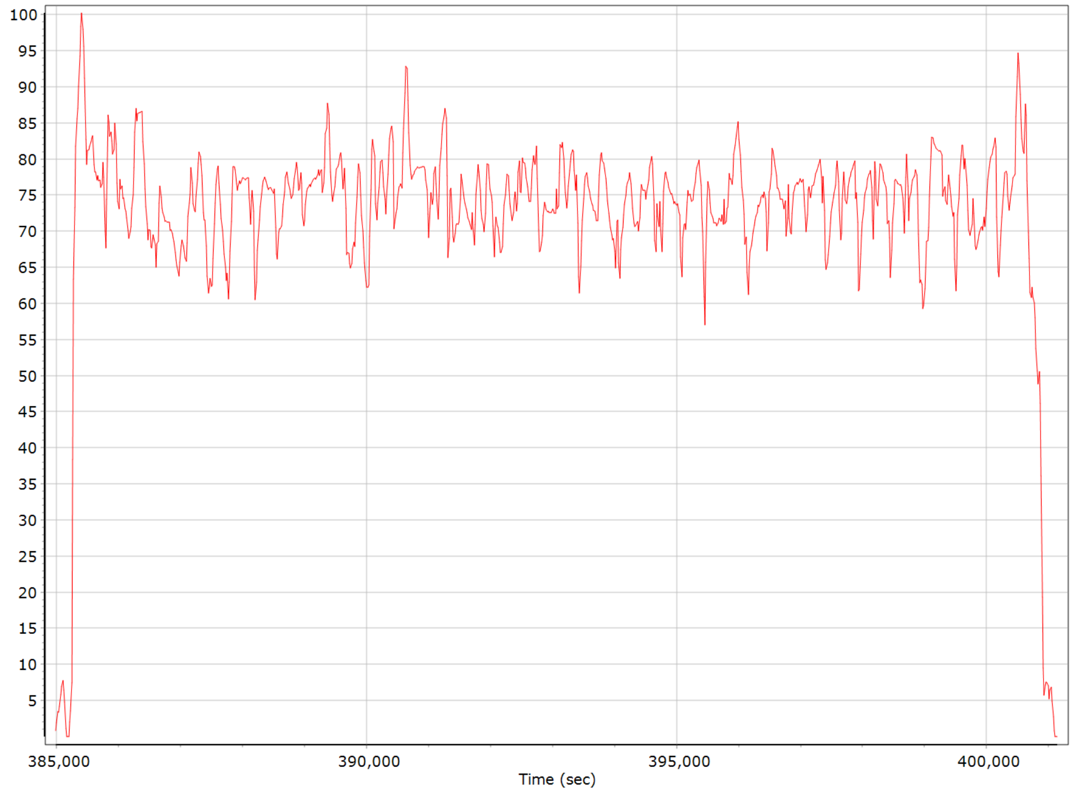
Down Velocity



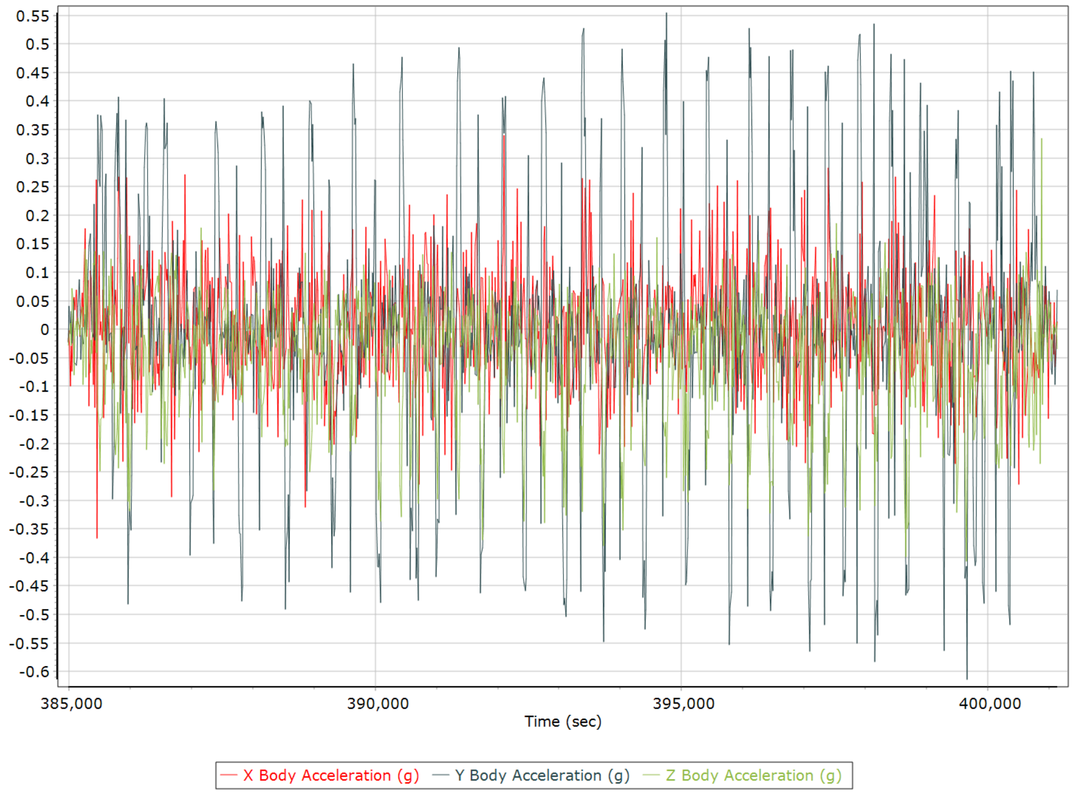
Total Speed



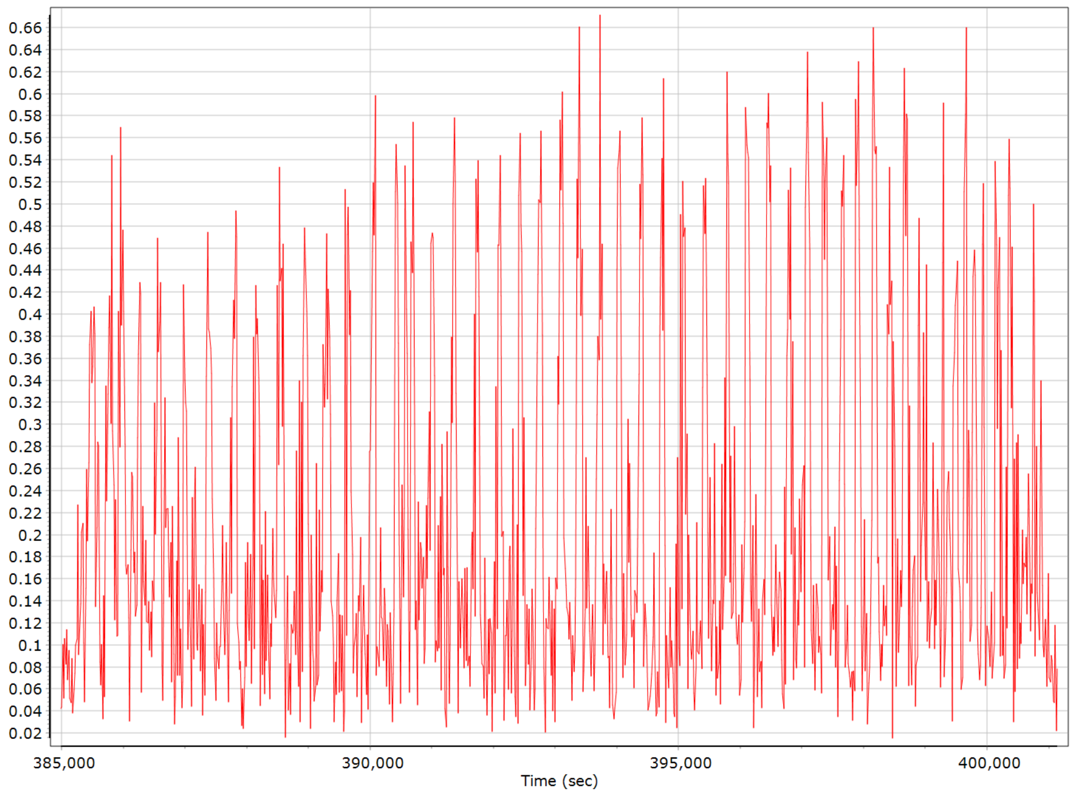
Ground Speed



Body Acceleration



Total Body Acceleration



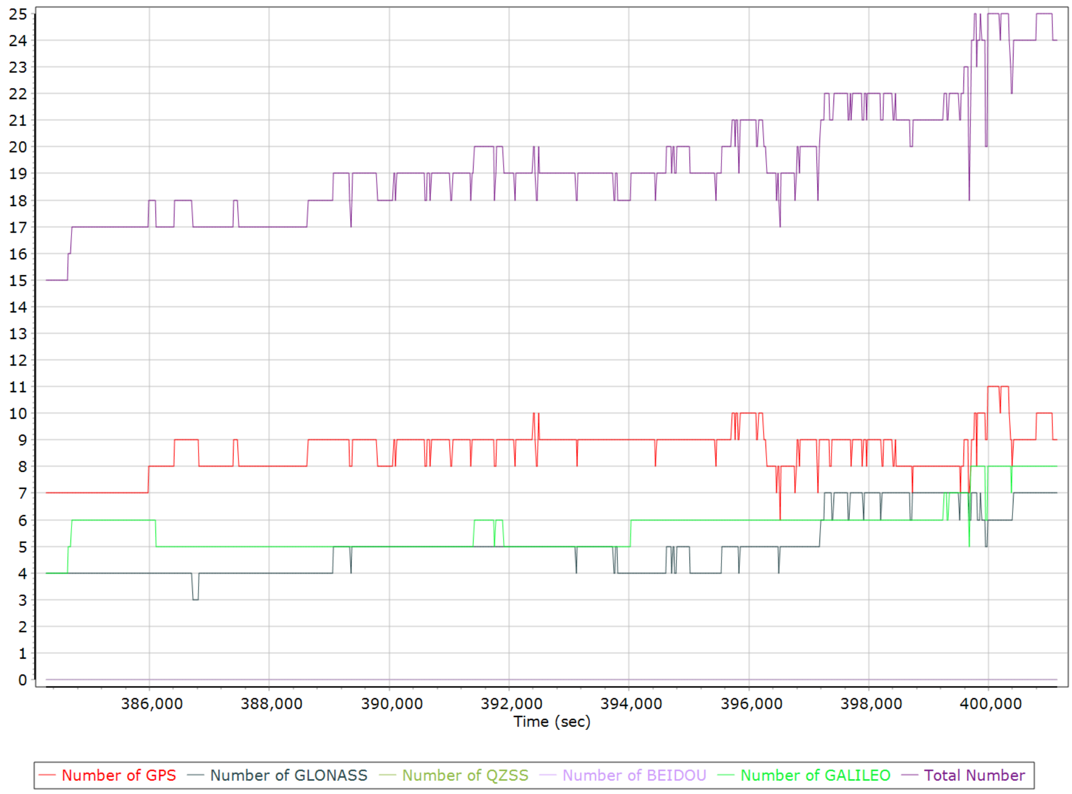
Body Angular Rate

GNSS QC

GNSS QC Statistics

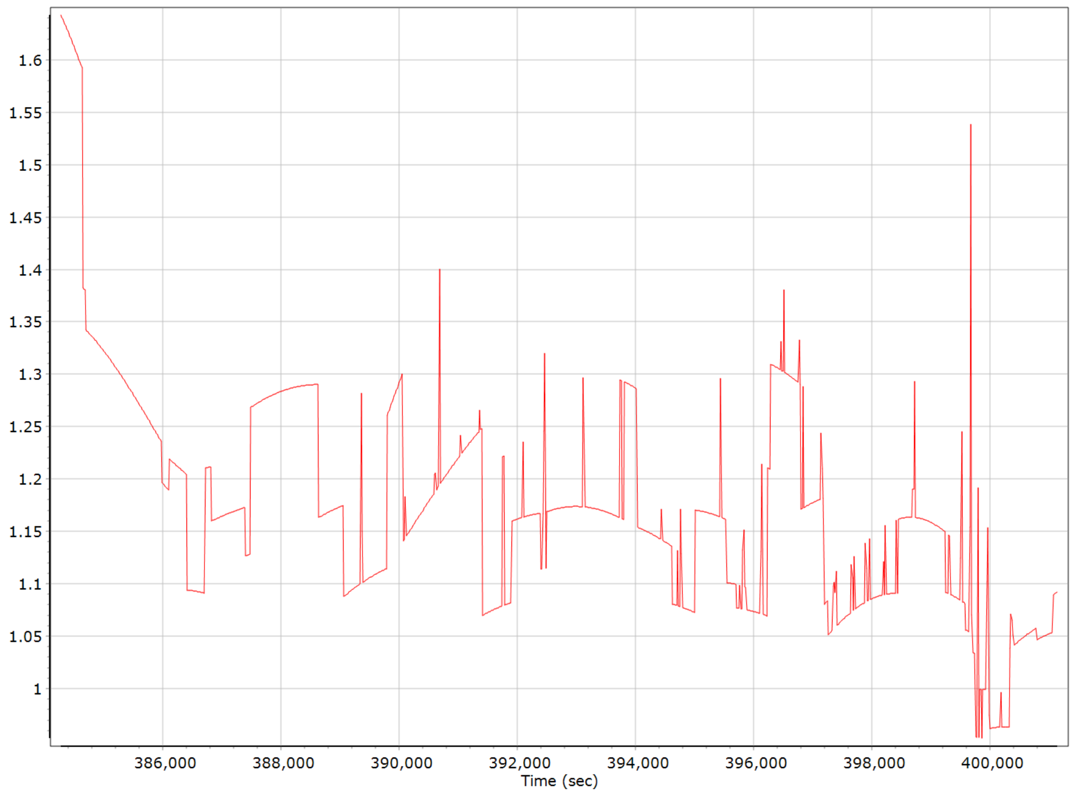
Statistics	Min	Max	Mean
Baseline length (km)	0.00	0.00	
Number of GPS SV	5	11	9
Number of GLONASS SV	3	7	5
Number of QZSS SV	0	0	0
Number of BEIDOU SV	0	0	0
Number of GALILEO SV	4	8	6
Total number of SV	13	25	19
PDOP	0.95	2.28	1.18
QC Solution Gaps	0.00	0.00	
Solution Type	Fixed	Float	No solution
Epoch (sec)	16947.00	0.00	0.00
Percentage	100.00	0.00	0.00

Num SVs in solution

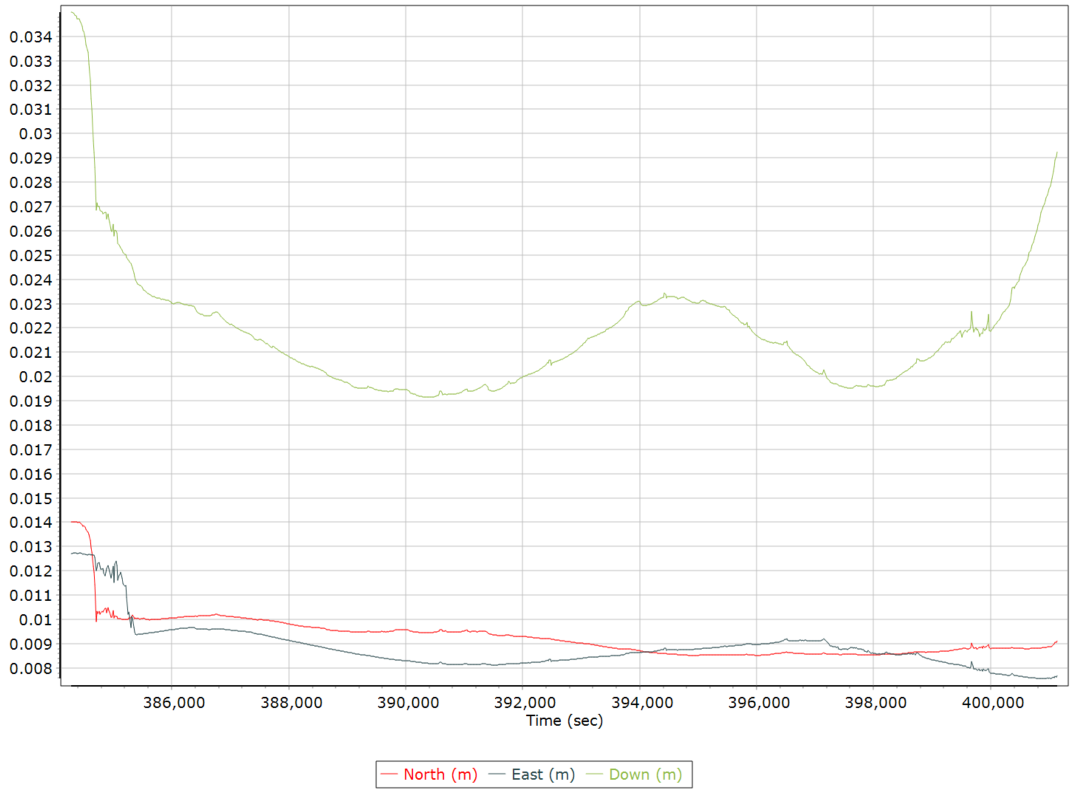


Forward/Reverse Separation

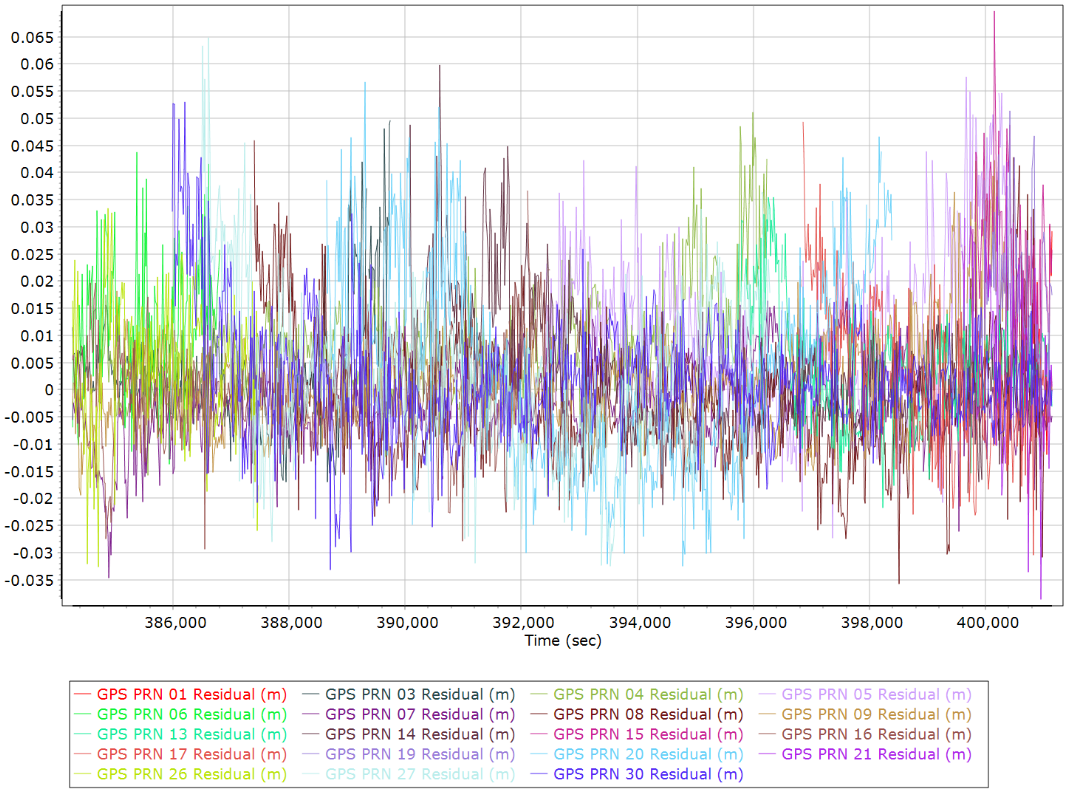
PDOP



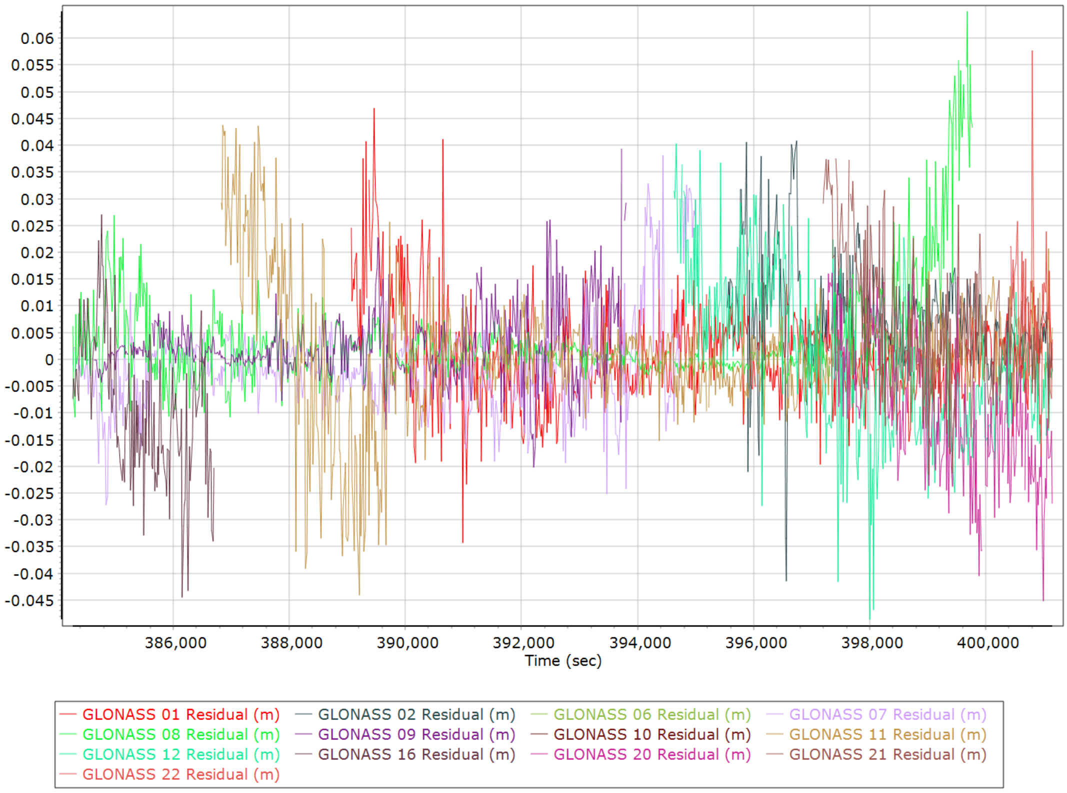
Estimated Position Accuracy



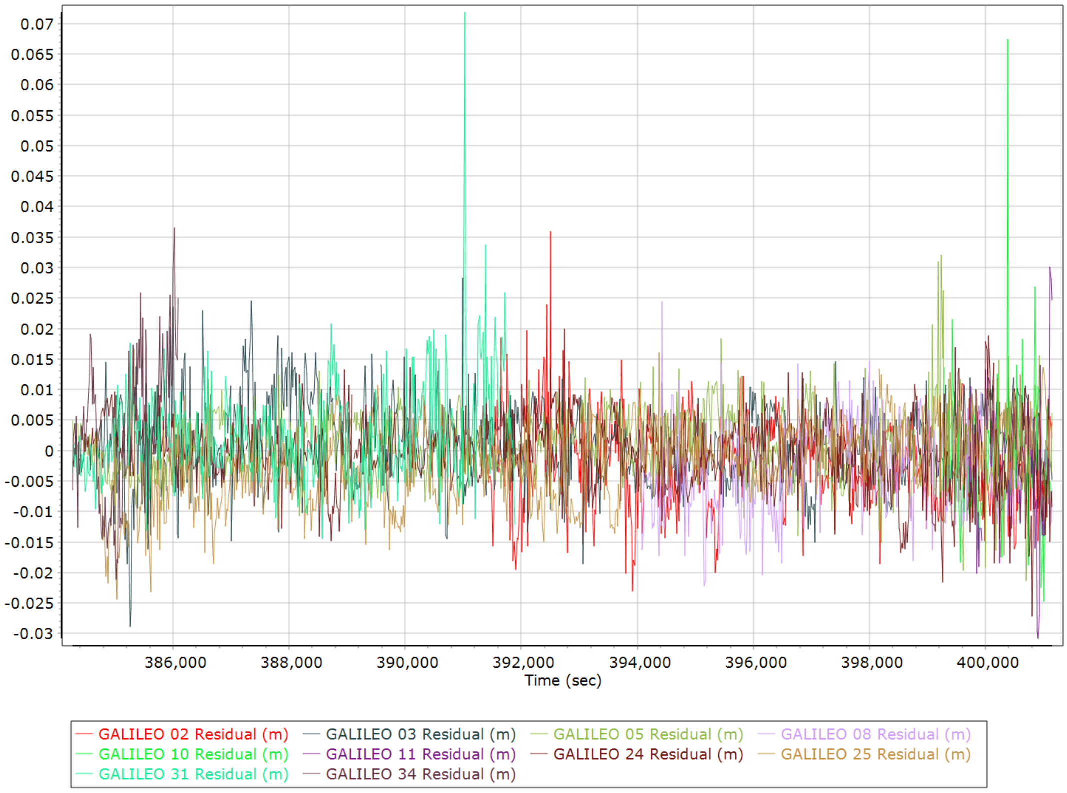
GPS Residuals



GLONASS Residuals



GALILEO Residuals



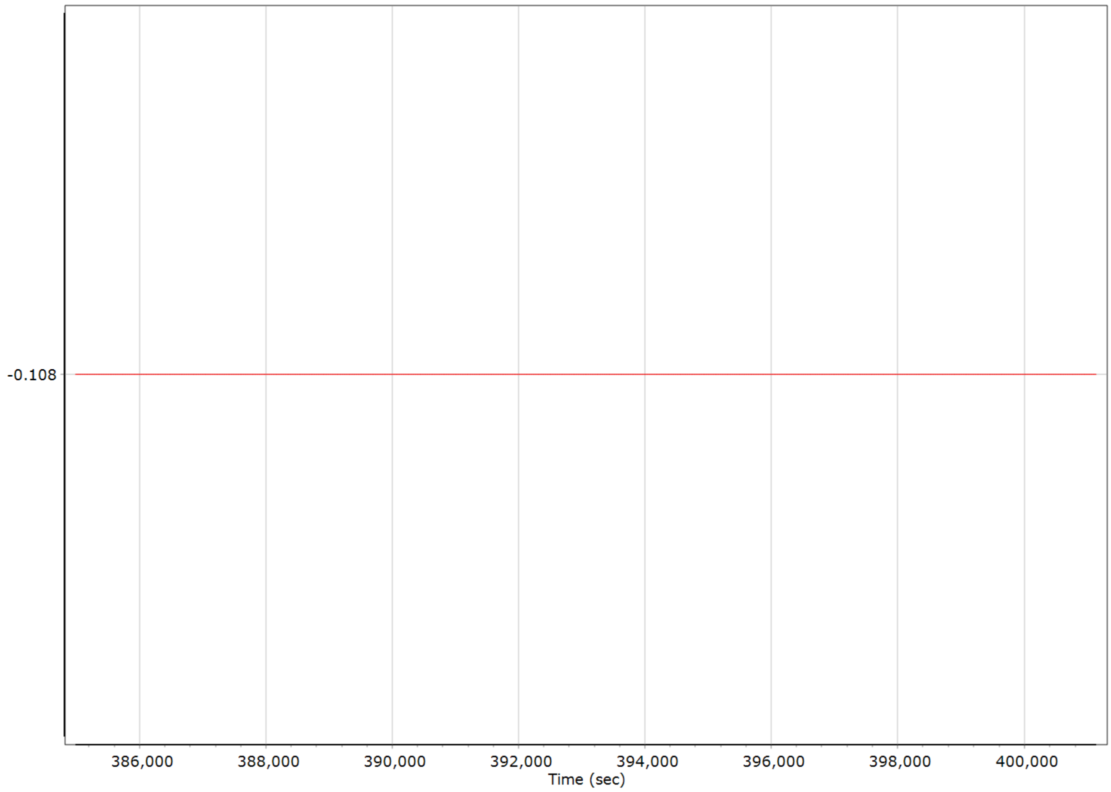
GNSS-Inertial Processor Configuration

Processing mode	IN-Fusion PP-RTX		
Stabilized mount	False		
Processing start time	384178.000 (4/20/2023 10:42:58 AM)		
Processing end time	401150.000 (4/20/2023 3:25:50 PM)		
Initial attitude source	Primary GNSS Track		
IMU Sensor Context	Processing with Onboard IMU		
Reference to IMU lever arm (m)	-0.034	-0.010	-0.374
Reference to IMU mounting angles (deg)	0.000	0.000	0.000
Reference to Primary GNSS lever arm (m)	-0.108	-0.621	-1.329
Reference to Primary GNSS lever arm std dev (m)	0.030	0.030	0.030
Aircraft to Reference mounting angles (deg)	0.000	0.000	0.000

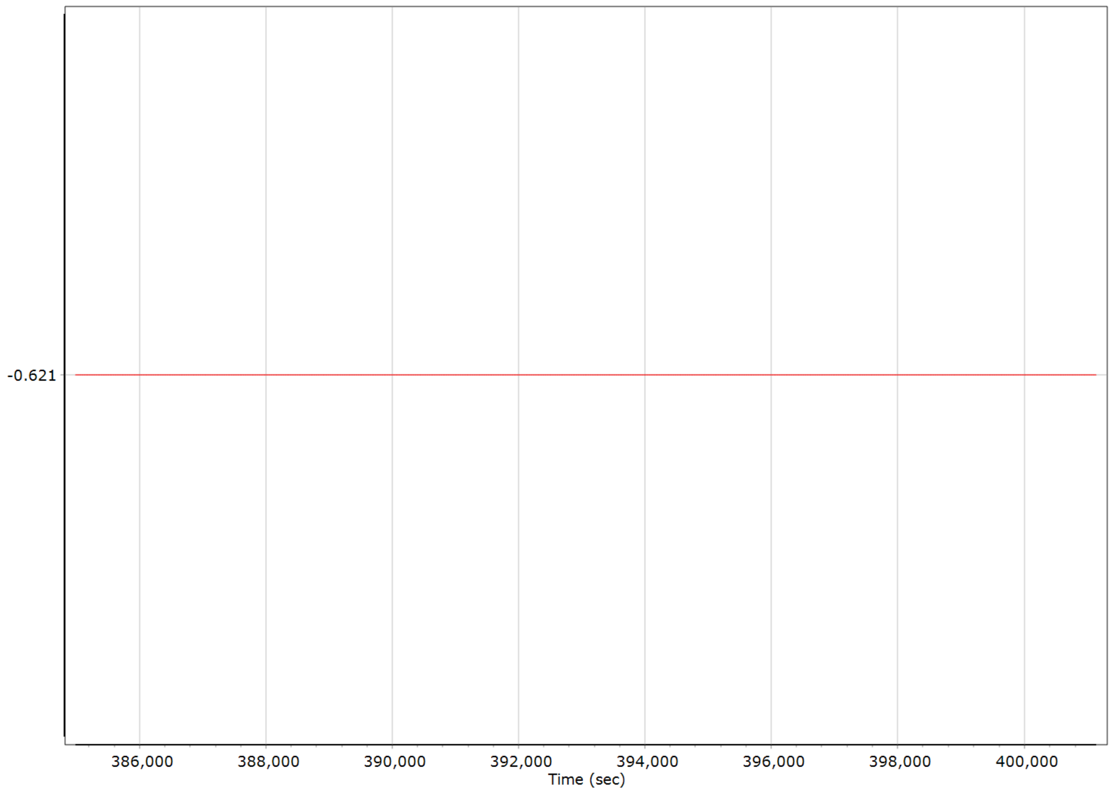
Calibrated Installation Parameters

Reference-Primary GNSS Lever Arm (m)

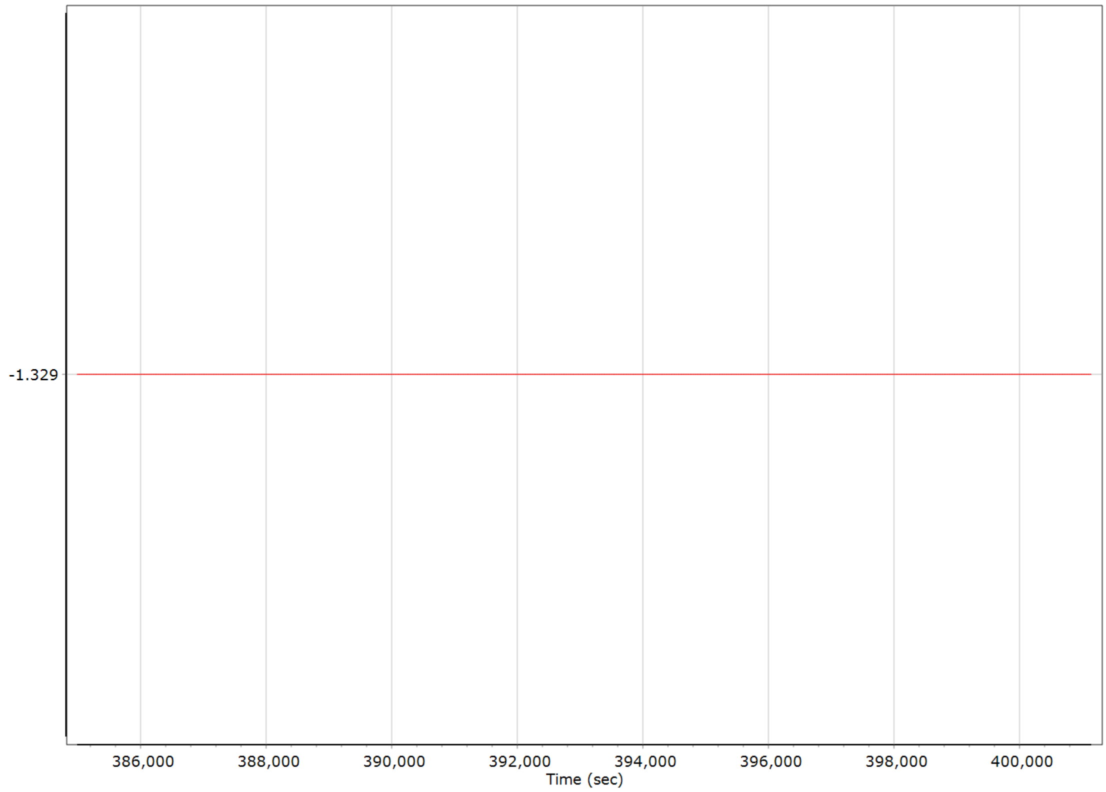
X Reference-Primary GNSS Lever Arm (m)



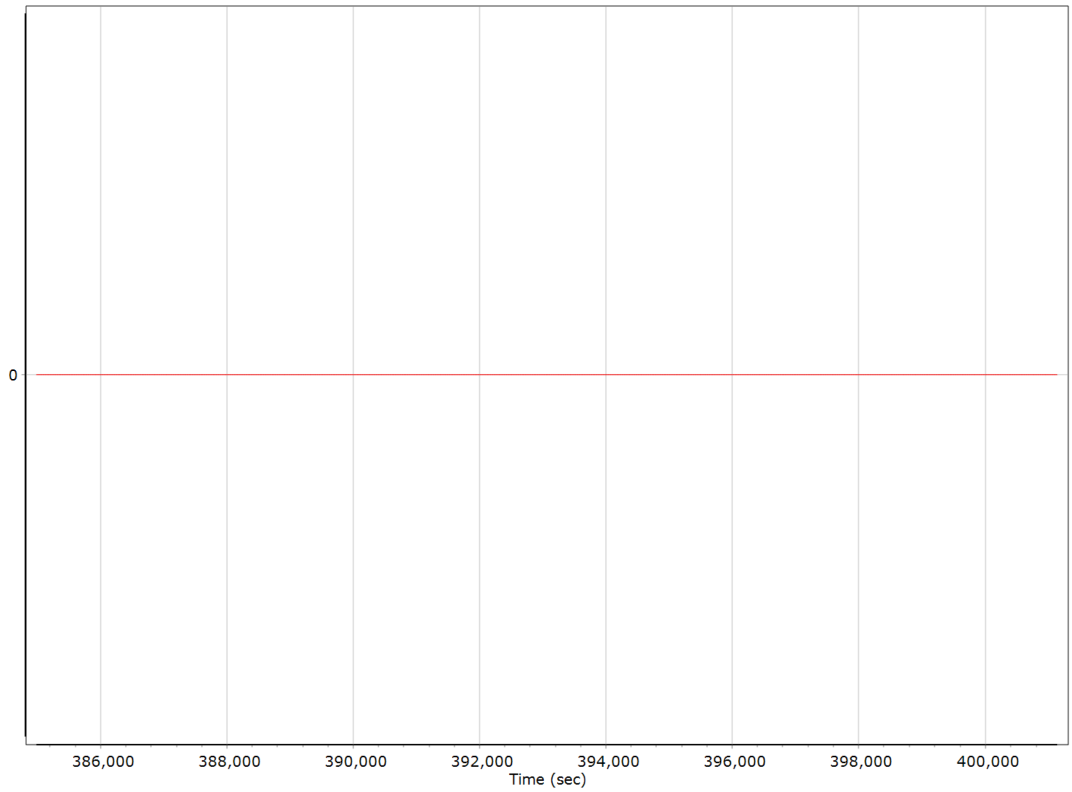
Y Reference-Primary GNSS Lever Arm (m)



Z Reference-Primary GNSS Lever Arm (m)



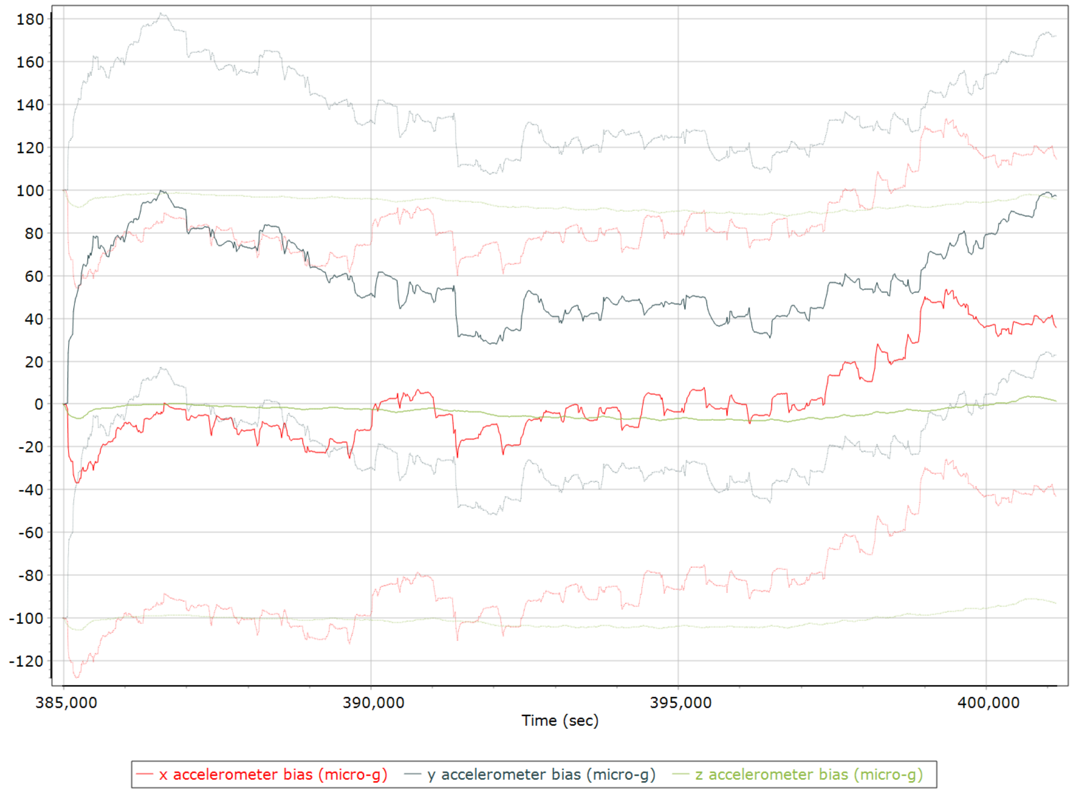
Reference-Primary GNSS Lever Arm Figure of Merit



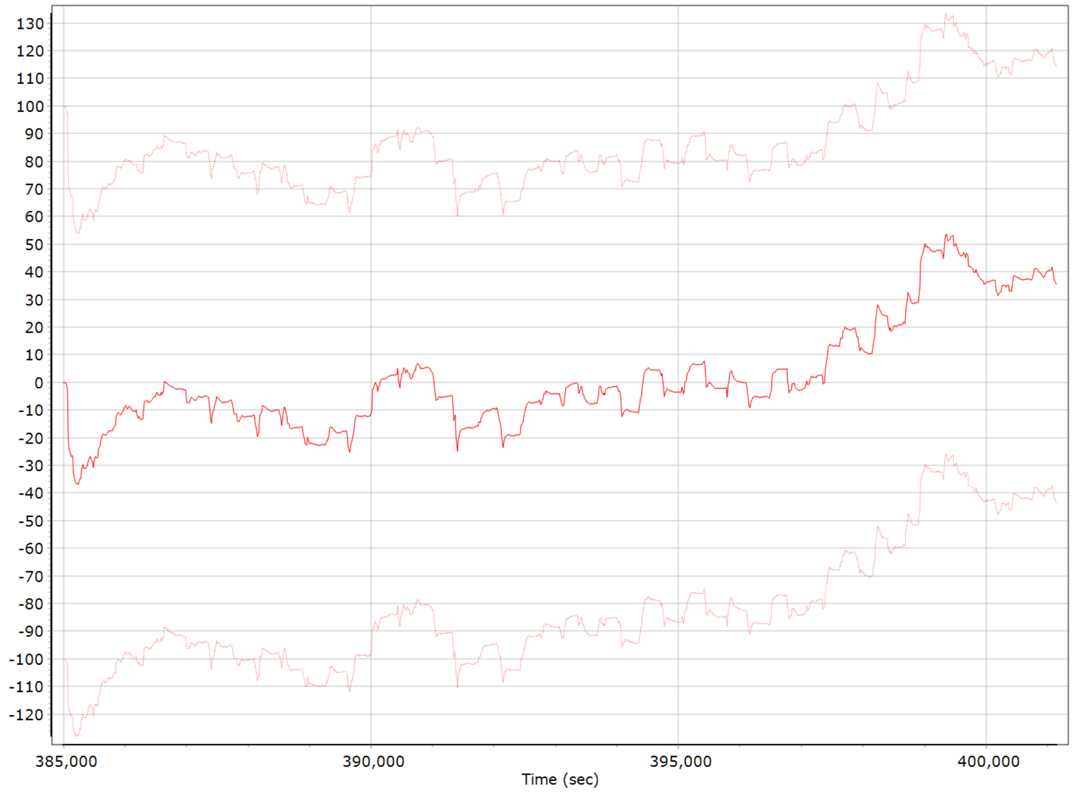
IN-Fusion QC

Forward Processed Estimated Errors, Reference Frame

Accelerometer Bias (micro-g)

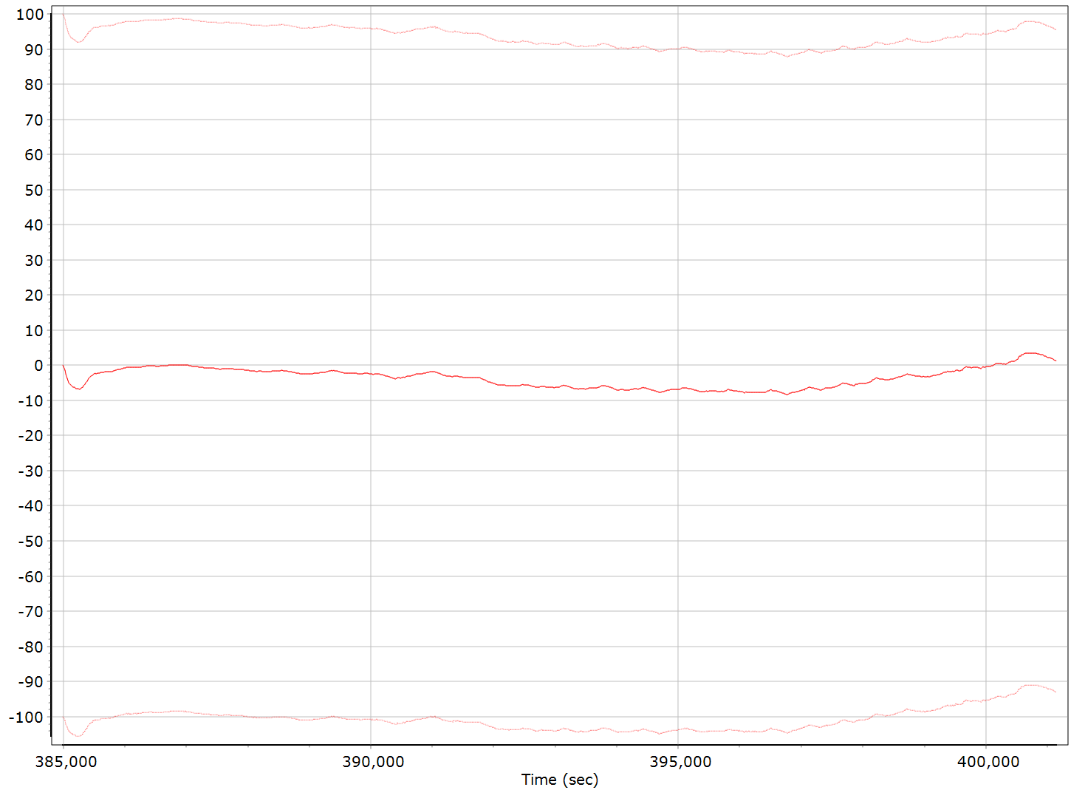


X Accelerometer Bias (micro-g)



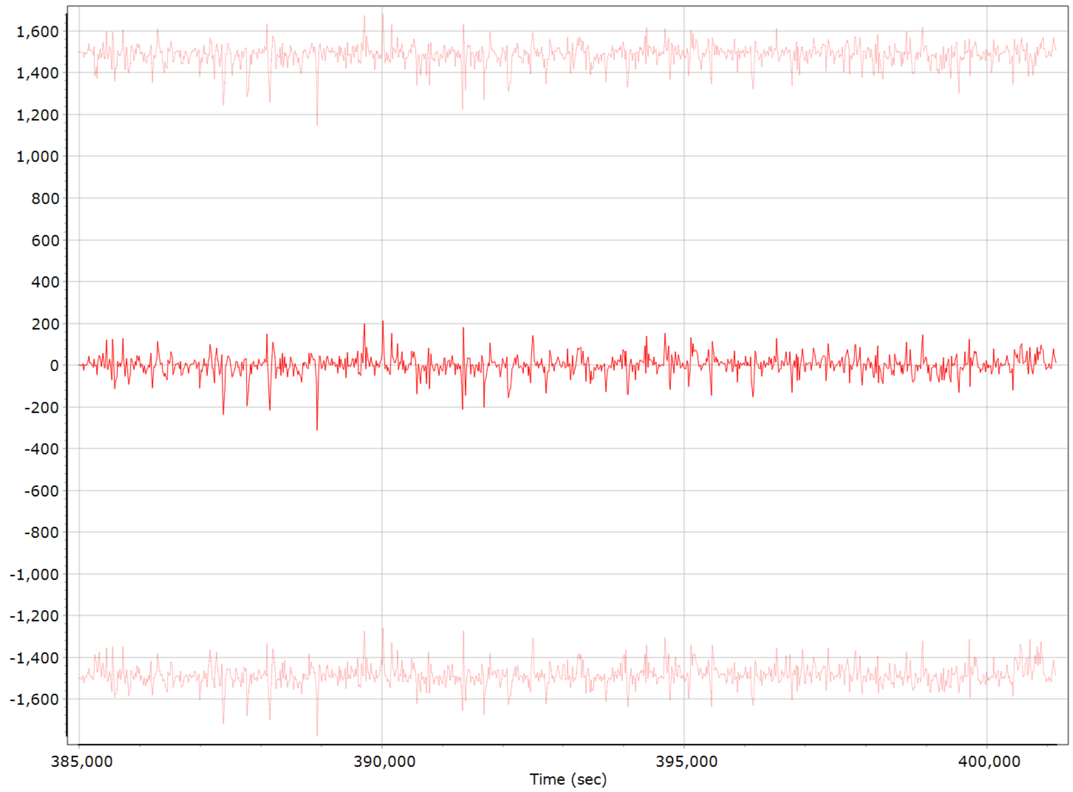
Y Accelerometer Bias (micro-g)

Z Accelerometer Bias (micro-g)



Accelerometer Scale Error (ppm)

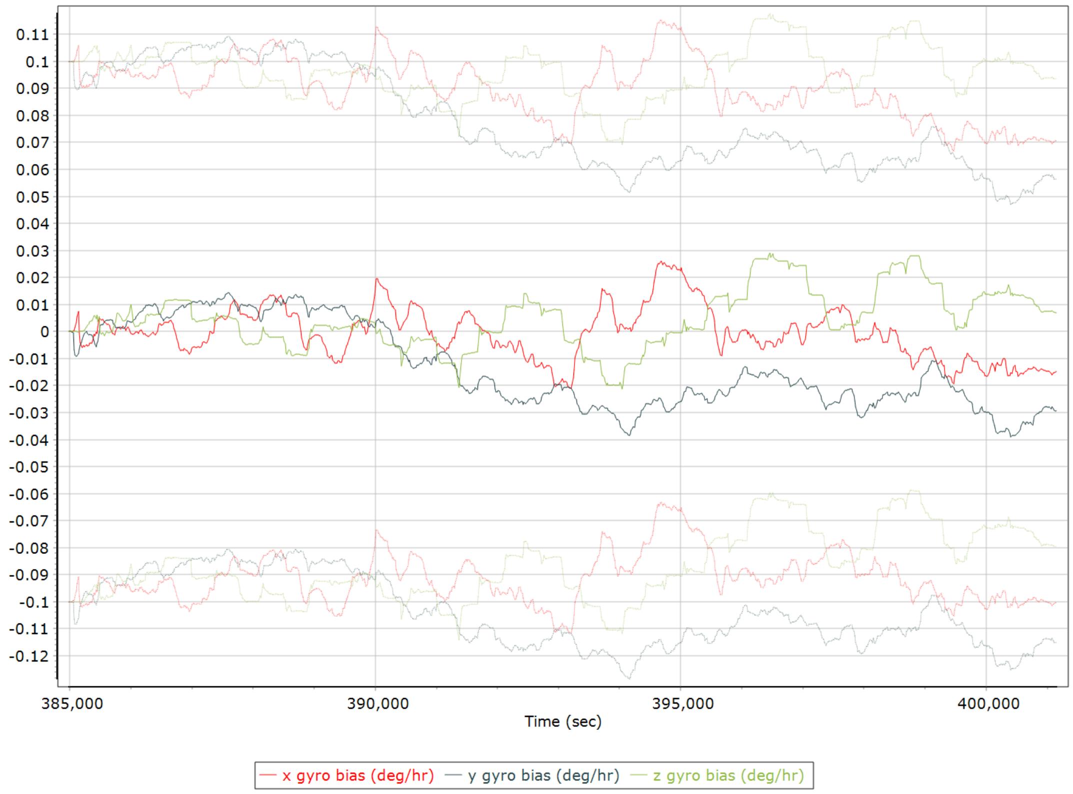
X Accelerometer Scale Error (ppm)



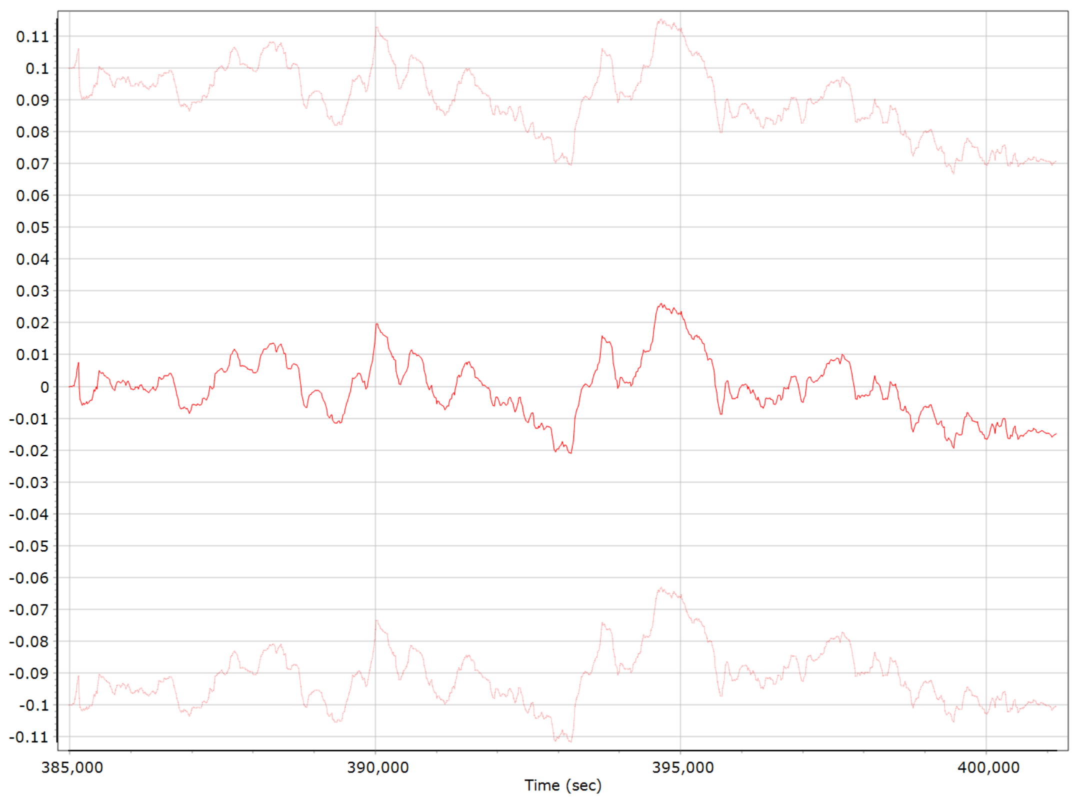
Y Accelerometer Scale Error (ppm)

Z Accelerometer Scale Error (ppm)

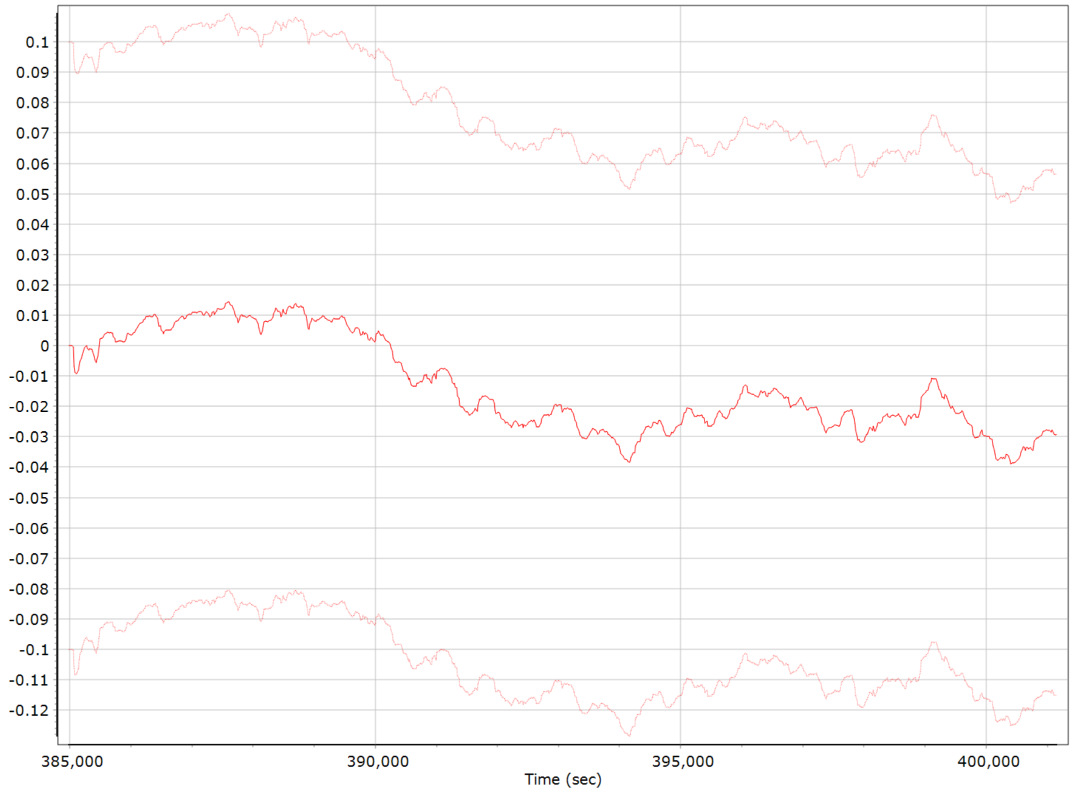
Gyro Bias (deg/h)



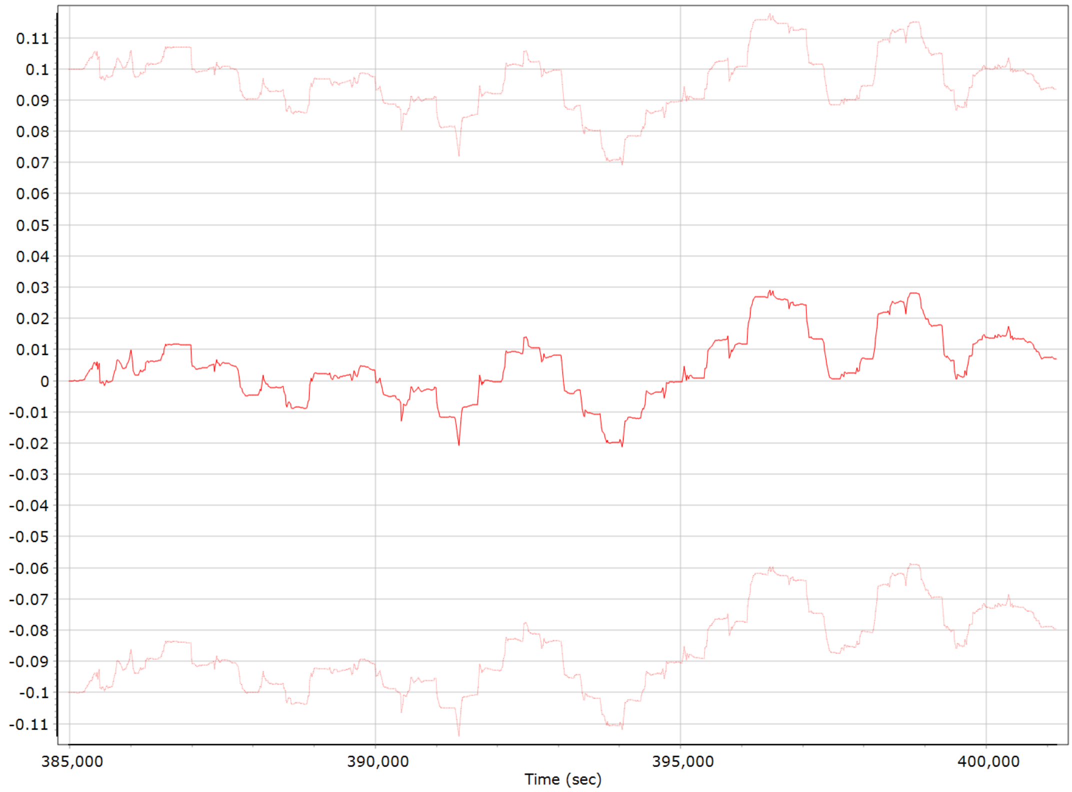
X Gyro Bias (deg/h)



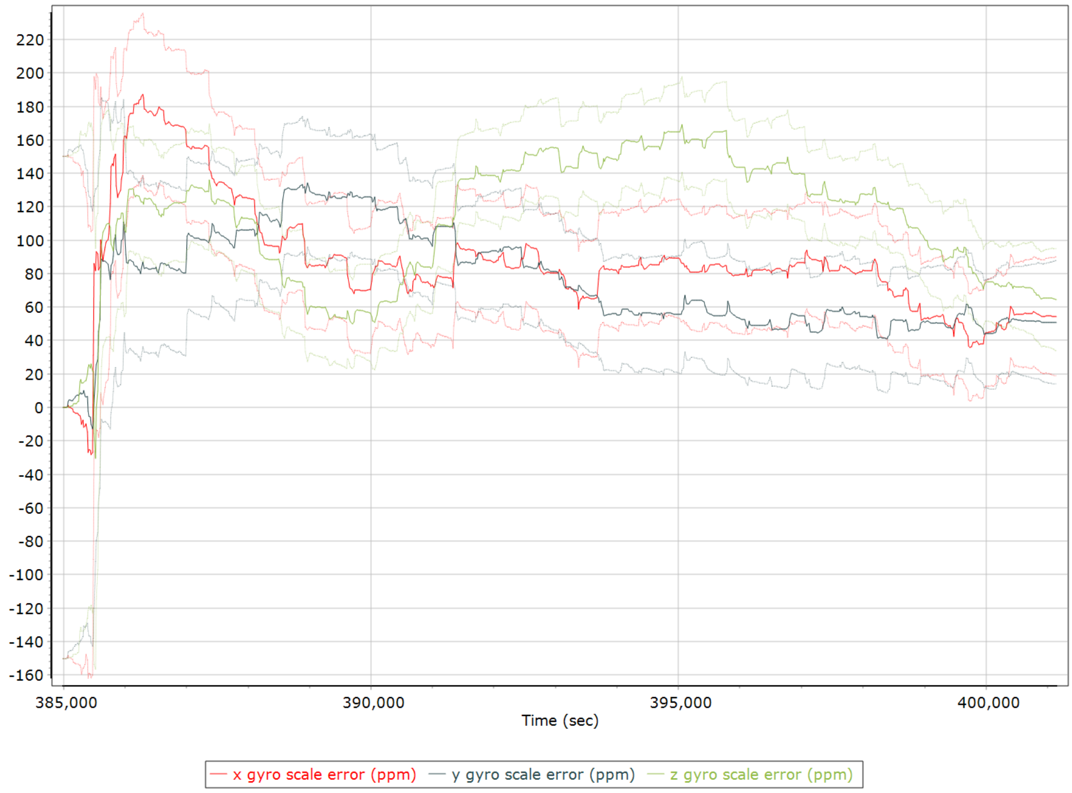
Y Gyro Bias (deg/h)



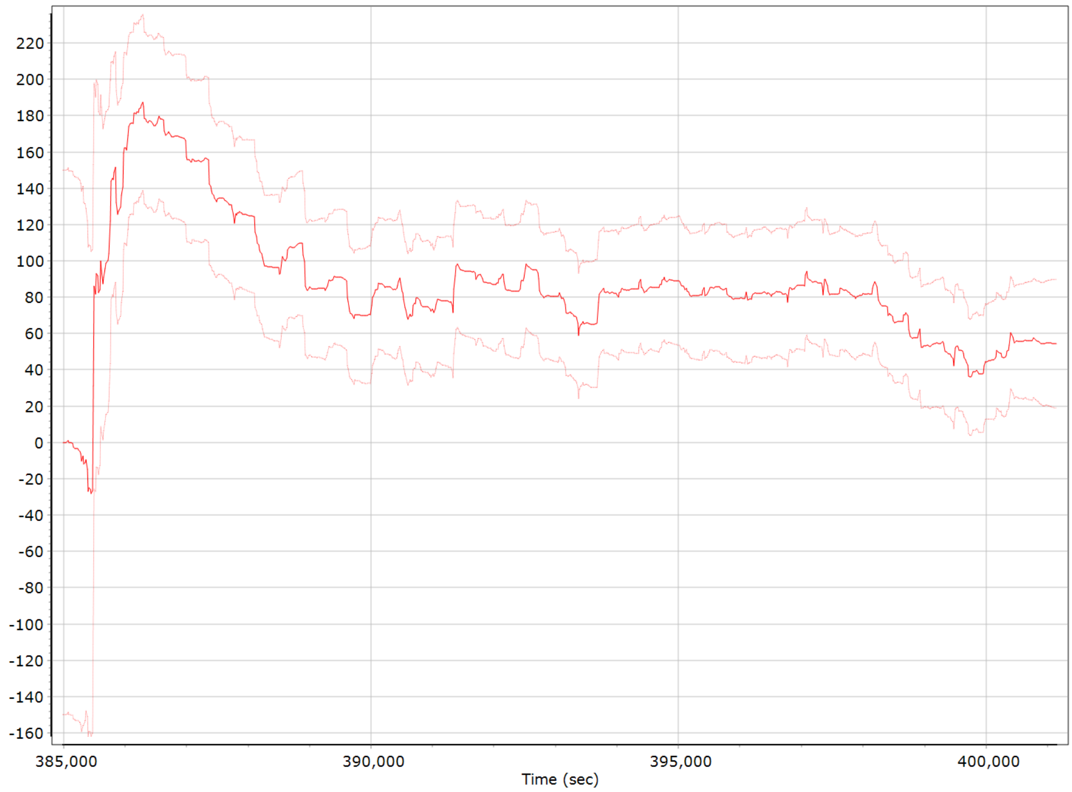
Z Gyro Bias (deg/h)



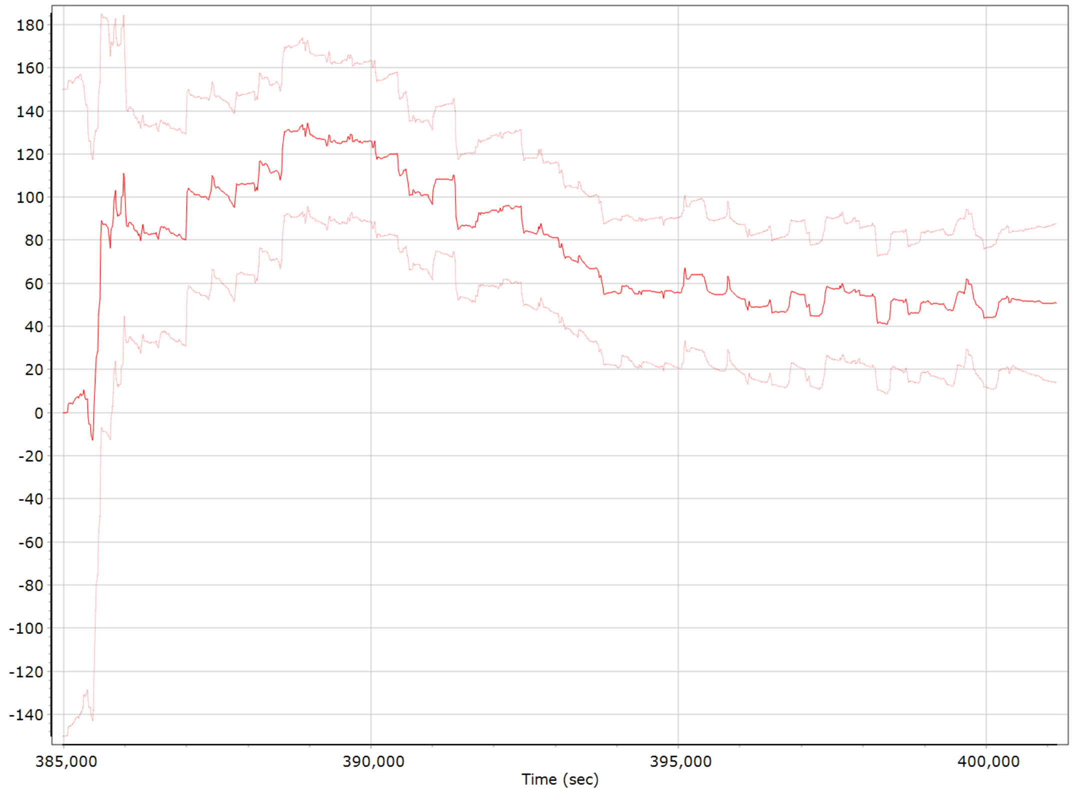
Gyro Scale Error (ppm)



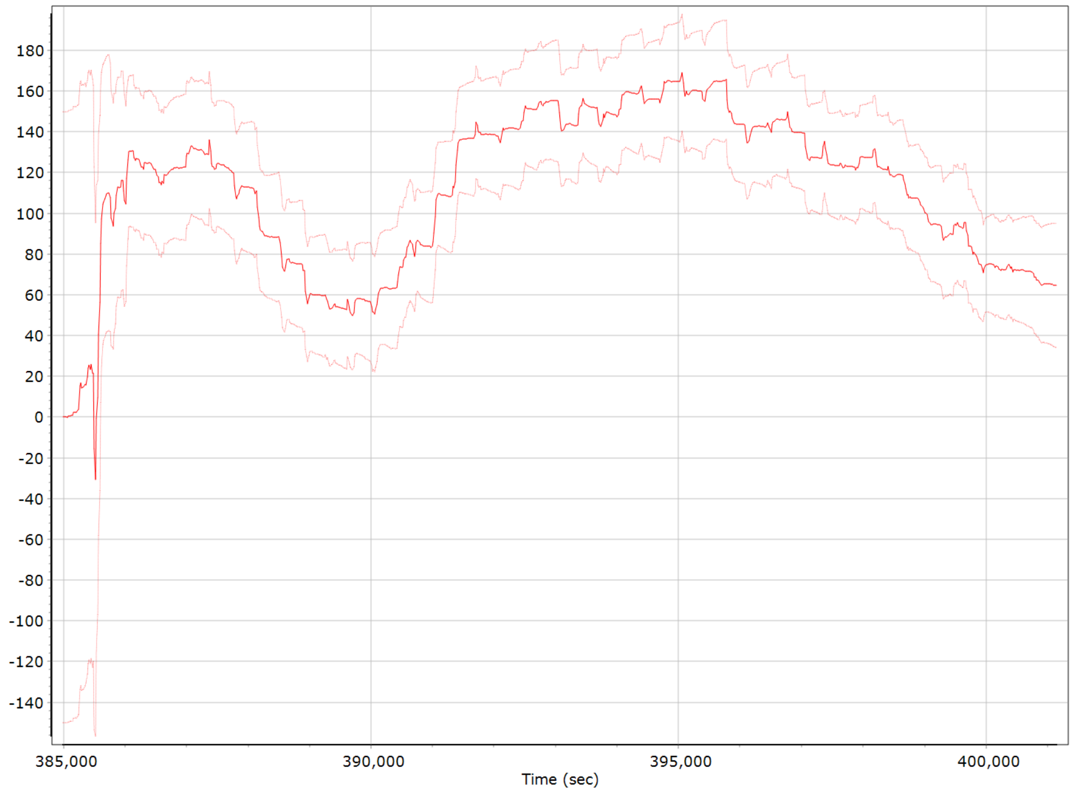
X Gyro Scale Error (ppm)



Y Gyro Scale Error (ppm)

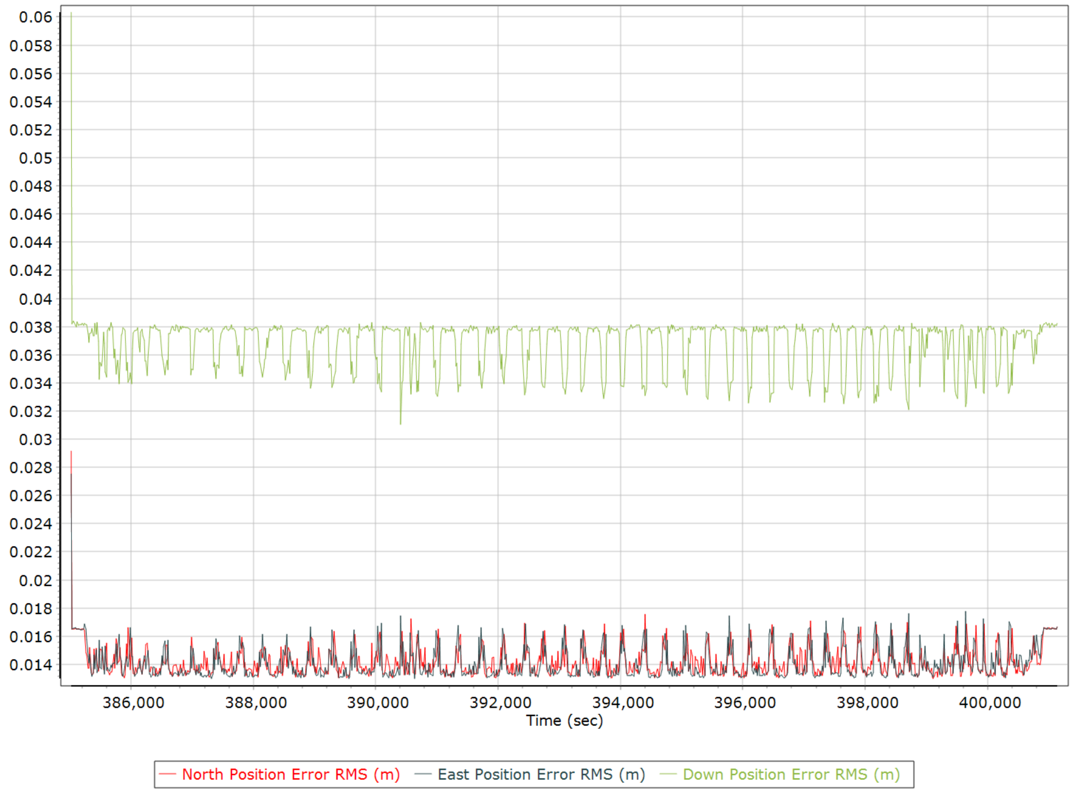


Z Gyro Scale Error (ppm)

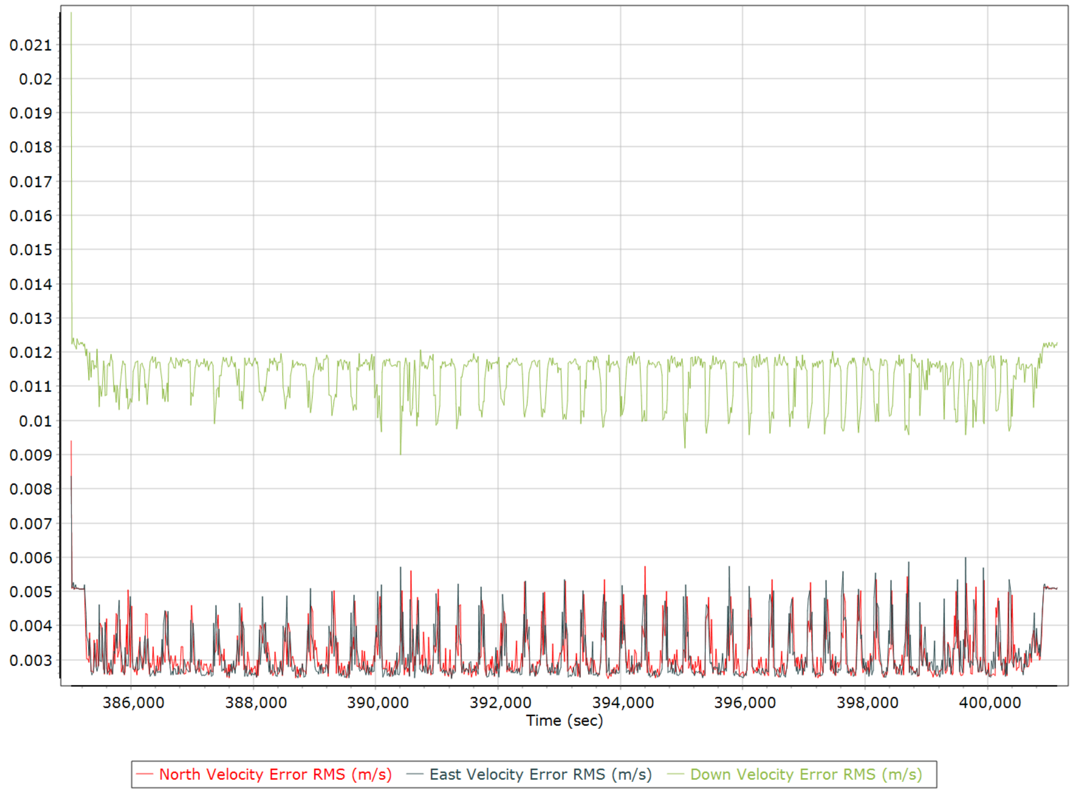


Smoothed Performance Metrics

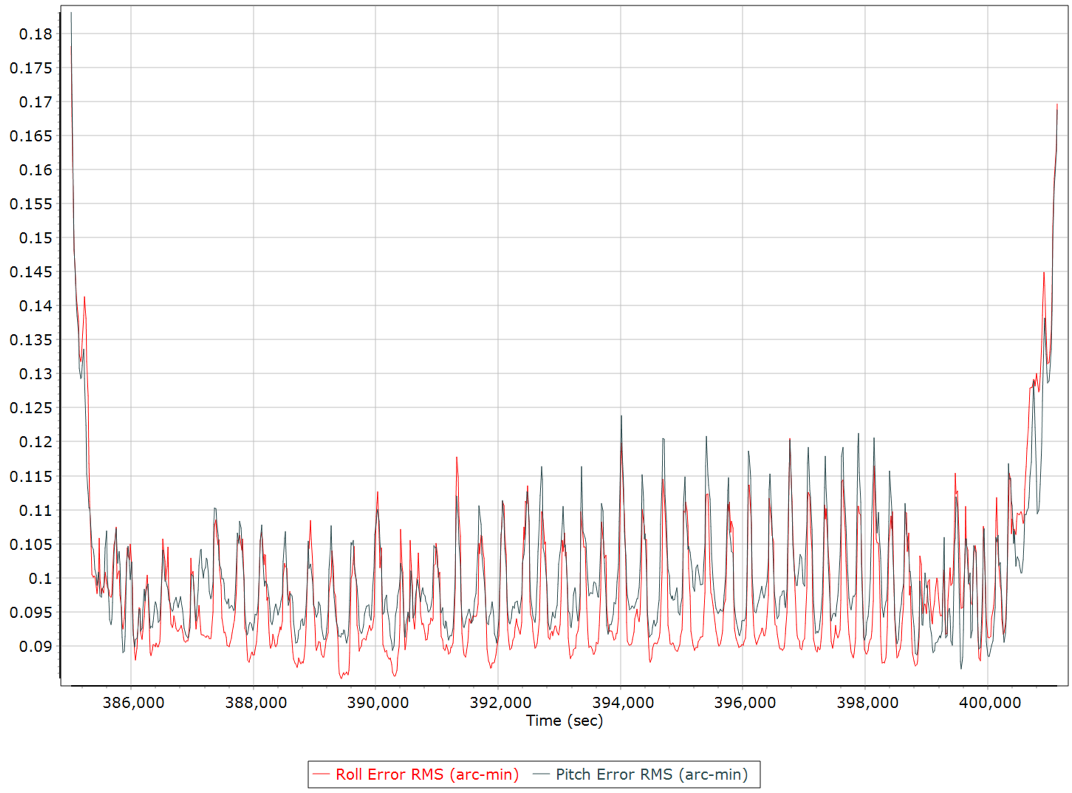
Position Error RMS (m)



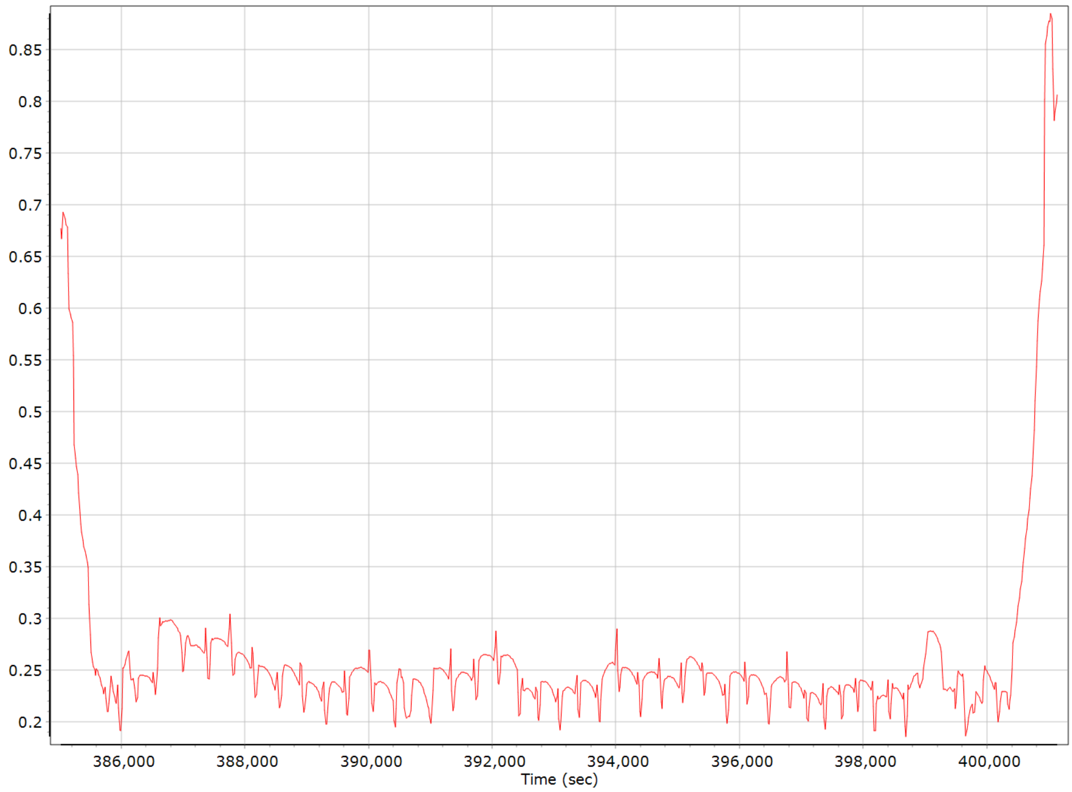
Velocity Error RMS (m/s)



Roll/Pitch Error RMS (arc-min)



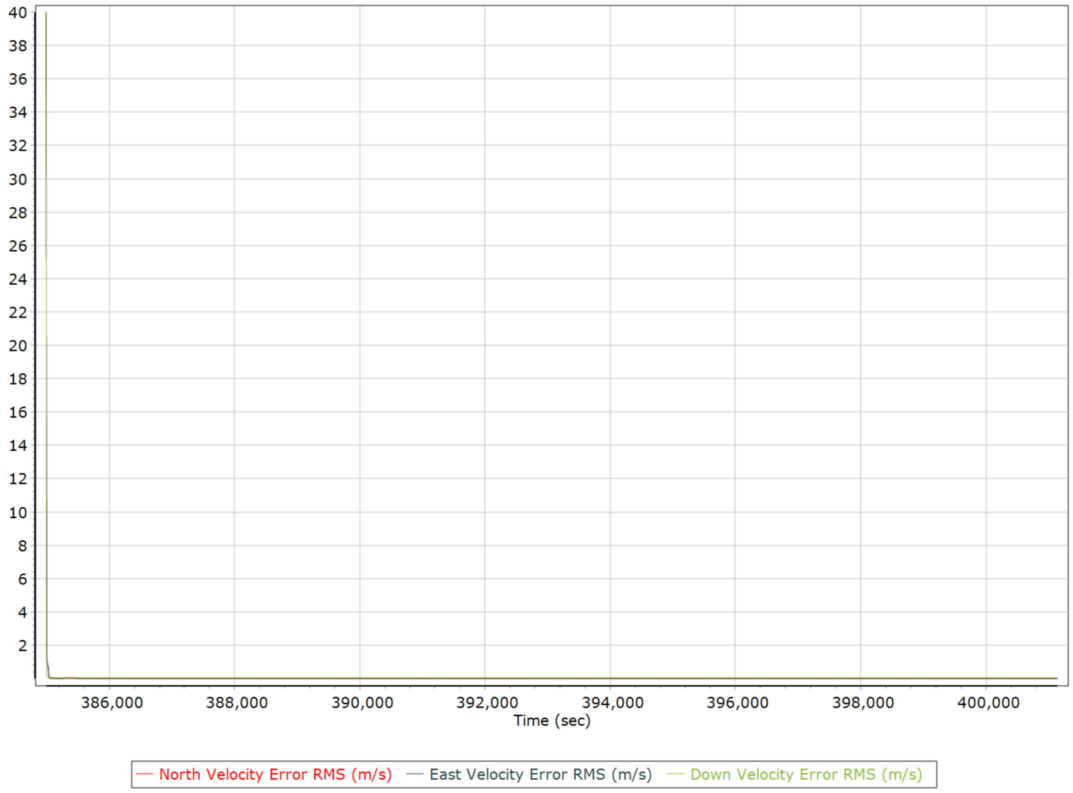
Heading Error RMS (arc-min)



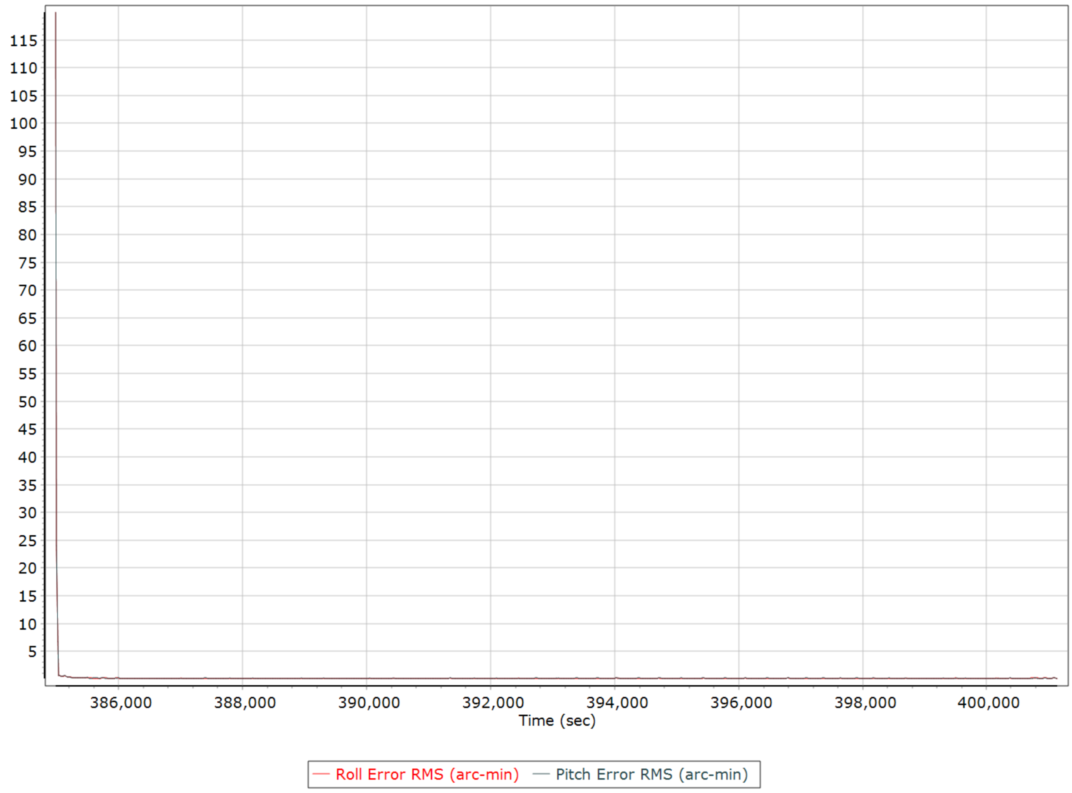
Forward Processed Performance Metrics

Position Error RMS (m)

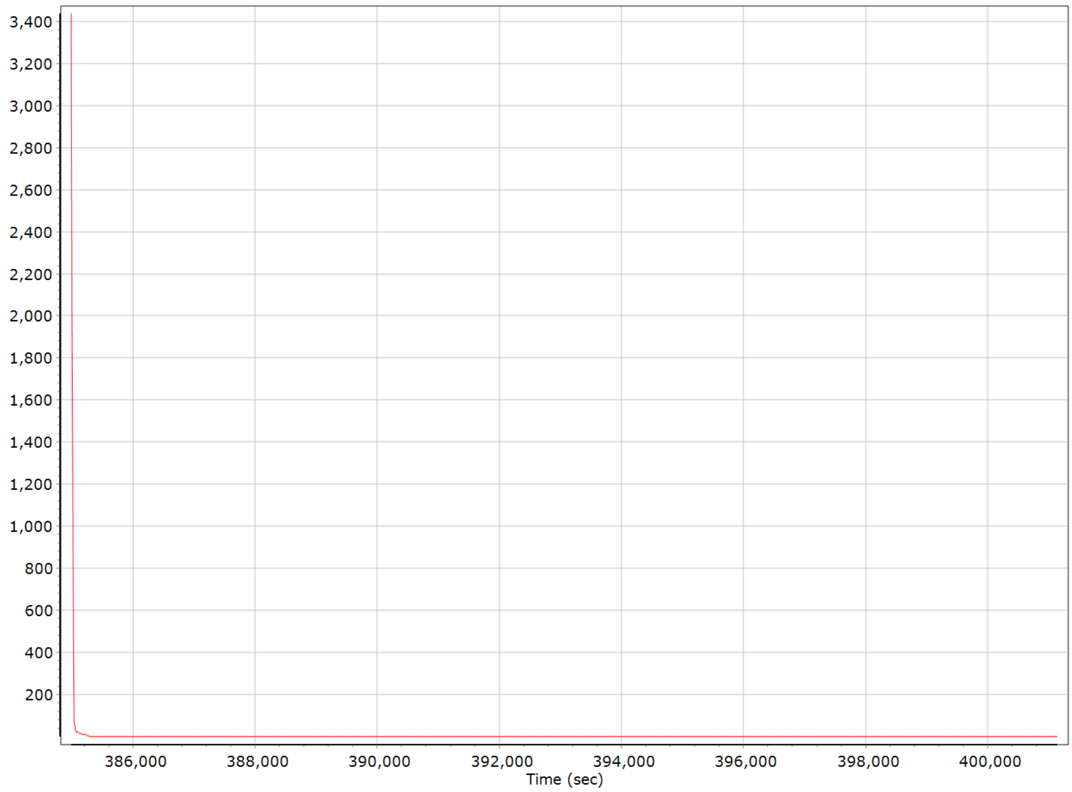
Velocity Error RMS (m/s)



Roll/Pitch Error RMS (arc-min)

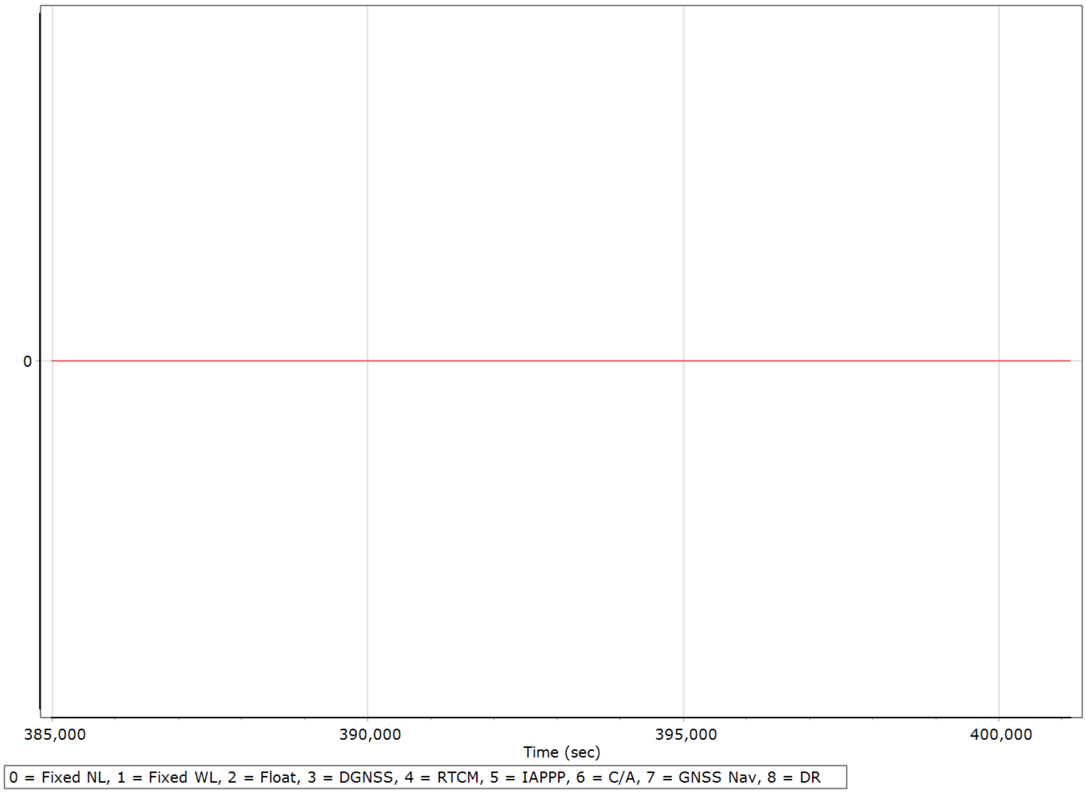


Heading Error RMS (arc-min)

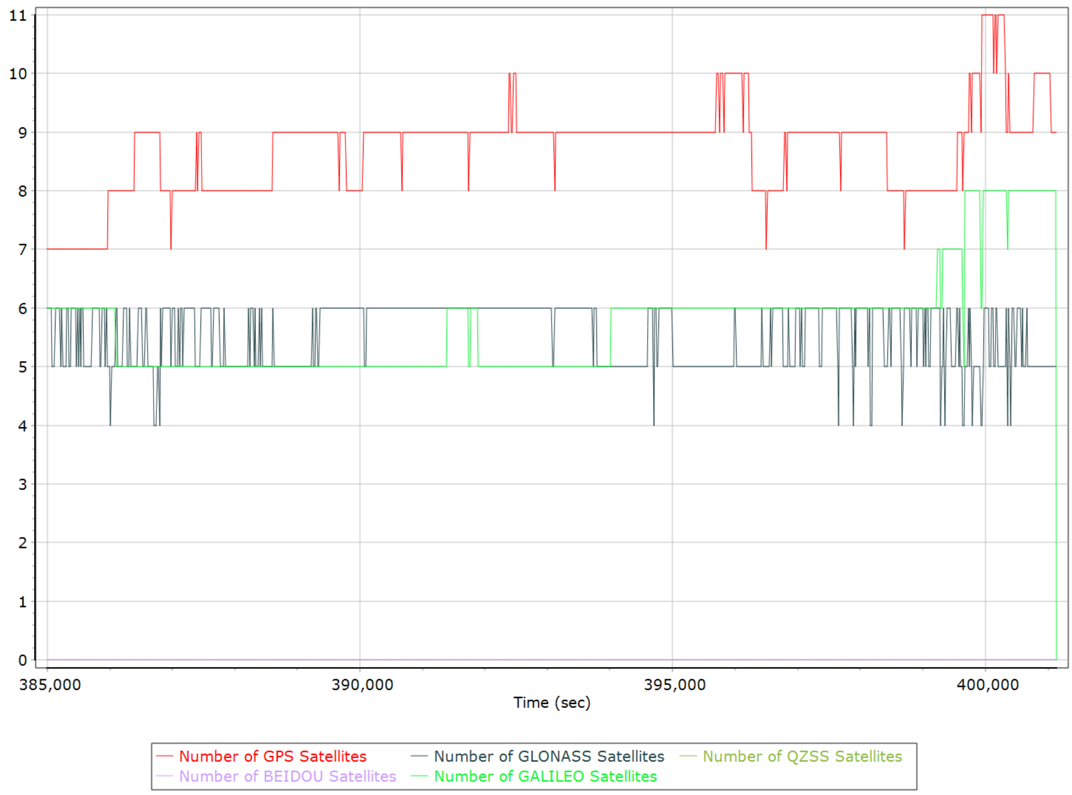


Forward Processed Solution Status

Processing Mode



Number of Satellites



Baseline Length