Generation of the Artemis I Best Estimated Trajectory (BET)

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OVERVIEW

Overview

- **Mission intro and BET framework overview**
  - Framework limitations
  - Hurdles and future considerations
- **Preprocessing**
  - Inertial Measurement Unit (IMU) data
  - GPS data
  - External (not on-board) data status
- **Flight data analysis**
- **Summary and concluding remarks**

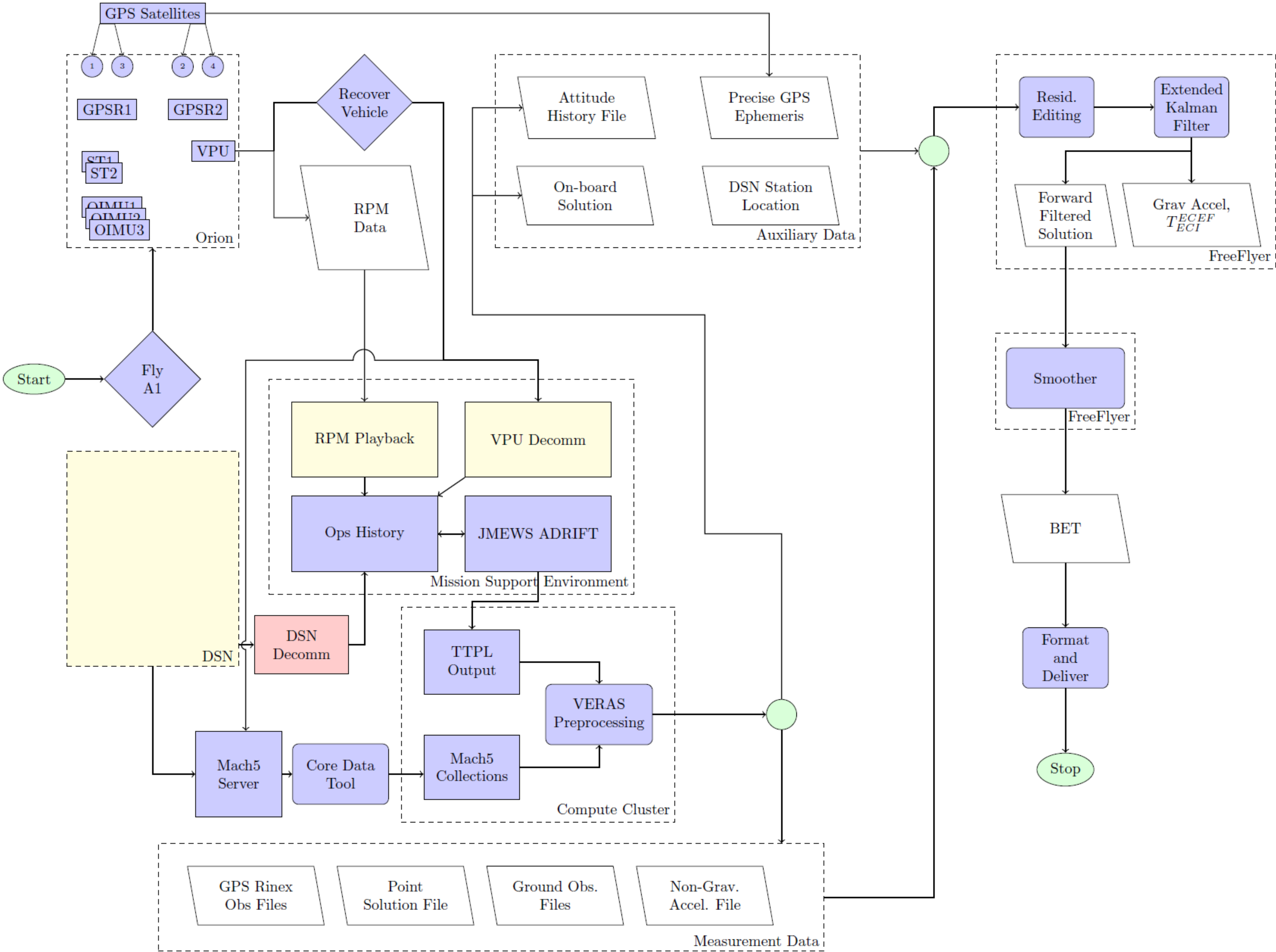
THE ARTEMIS I MISSION

The Artemis I Mission

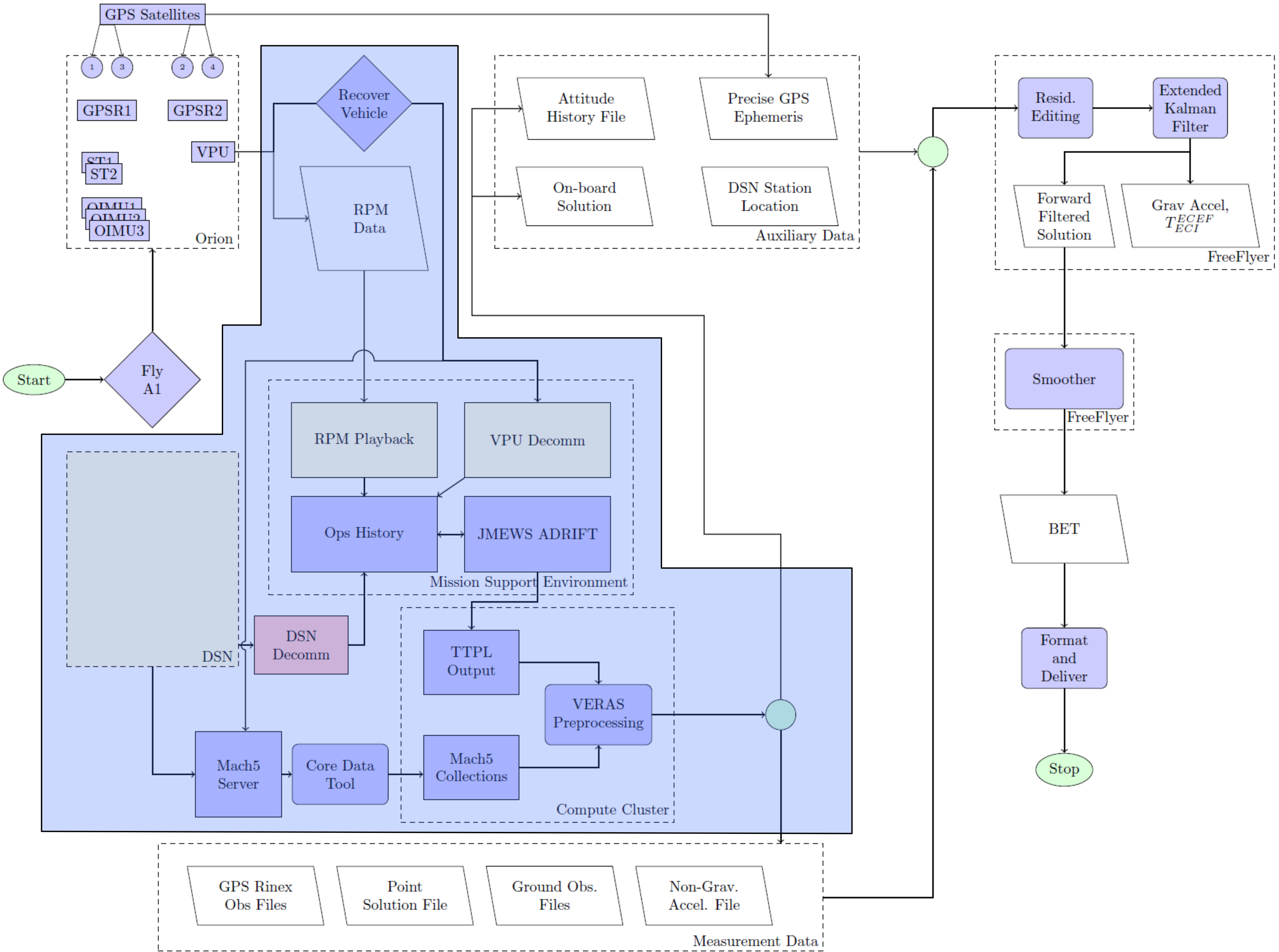
- **Artemis I – the maiden voyage**
  - Liftoff: November 16, 2022
  - Splashdown: December 11, 2022
  - ## Flight test objectives (FTOs) + Developmental flight test objectives (DFTOs)
- **The BET**
  - FTO/DFTO require “truth” to compare against
  - 25 days of data requires significant pre-processing
    - Low-rate data telemetered to ground any time communication is possible
    - High-rate recorded data is recovered via:
      - Real-time downlinks during the mission (roughly every 24 hours)
      - Extracted directly from the physical VPU
    - Sophisticated data delivery methods result in:
      - Data drop outs

The Artemis I Mission

- **The Program keeps moving**
  - Flight schedule requires analysis to be done ASAP
  - Accommodations have been made, but several techniques were required to properly process the flight data
- **This paper attempts to capture the full BET generation process**
  - An ideal workflow materialized very early on
  - Work strayed from the ideal flow in the middle of the mission
  - This paper attempts to outline this nominal work flow
    - As the nominal work flow is detailed, so are the necessary work-arounds
    - This is a knowledge capture for future Artemis BET efforts
    - This is also an effort to ID forward work



GPS Satellites
1
3
2
4
GPSR1
GPSR2
VPU
ST1
ST2
OIMU1
OIMU2
OIMU3
Orion
Recover Vehicle
RPM Data
Attitude History File
Precise GPS Ephemeris
On-board Solution
DSN Station Location
Auxiliary Data
Resid. Editing
Extended Kalman Filter
Forward Filtered Solution
Grav Accel, T_{ECI}^{ECEF}
FreeFlyer
Start
Fly A1
RPM Playback
VPU Decomm
Ops History
JMEWS ADRIFT
Mission Support Environment
Smoother
FreeFlyer
BET
DSN
DSN Decomm
TTPL Output
VERAS Preprocessing
Mach5 Collections
Compute Cluster
Format and Deliver
Stop
Mach5 Server
Core Data Tool
GPS Rinex Obs Files
Point Solution File
Ground Obs. Files
Non-Grav. Accel. File
Measurement Data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Non-Grav. Accel. File
Measurement Data

Data Acquisition, Extraction and Decommutation

- **Data capture is inherently difficult for any long duration mission**
  - Data transmittal is at the mercy of significant constraints
  - Low-rate data is telemetered in real-time whenever a communication link is present
    - This data is recorded in real-time on the ground
  - High-rate data is recorded on-board the vehicle and downlinked periodically
    - Due to storage constraints, this data is overwritten circularly
  - The high-rate data is critical for post-flight analysis
    - Heavily compressed to minimize bandwidth consumption
    - Decommutation/decompression of data is necessary, but complicated

Data Acquisition, Extraction and Decommutation

- **On-board, data is sampled and processed by the flight computer**
  - All samples are assigned a set of metadata to assist in data transfer
    - Each piece of data is assigned a unique identifier (CUI)
    - CUIs are assigned to groups referred to as packing maps
  - Packing maps generally consist of similar data to be downlinked together
    - Telemetry packing maps are downlinked in real-time
    - Recorded packing maps are downloaded together
    - At every 40 Hz cycle, these packing maps are constructed into a single digital exchange message (DEM)
    - The flight computer time stamps each DEM as they are created
      - Time stamps are encoded at the sub-microsecond level to provide a unique identifier associated with the packing map used in constructing the DEM
      - Specifically, these time stamps are used to reconstruct each DEM, providing a snapshot of a packing map at a specific time

Data Acquisition, Extraction and Decommutation

- **DEM construction happens at 40 Hz**
  - Data is generated asynchronously across the vehicle
  - Consequently, DEM time stamps can feasibly lag by up to a 40 Hz cycle
  - Time tags are recorded at the sensor and generally included in the packing map in order to obtain a more precise time tag
  - **Associating these time tags to their respective data samples is crucial, particularly in the case of IMU data**
- **This proved to be exceedingly difficult to do in the presence of multiple data sources**
  - Compounded by data compression
  - Two independent efforts underwent, both on the NASA and LM side

Data Acquisition Effort End Product

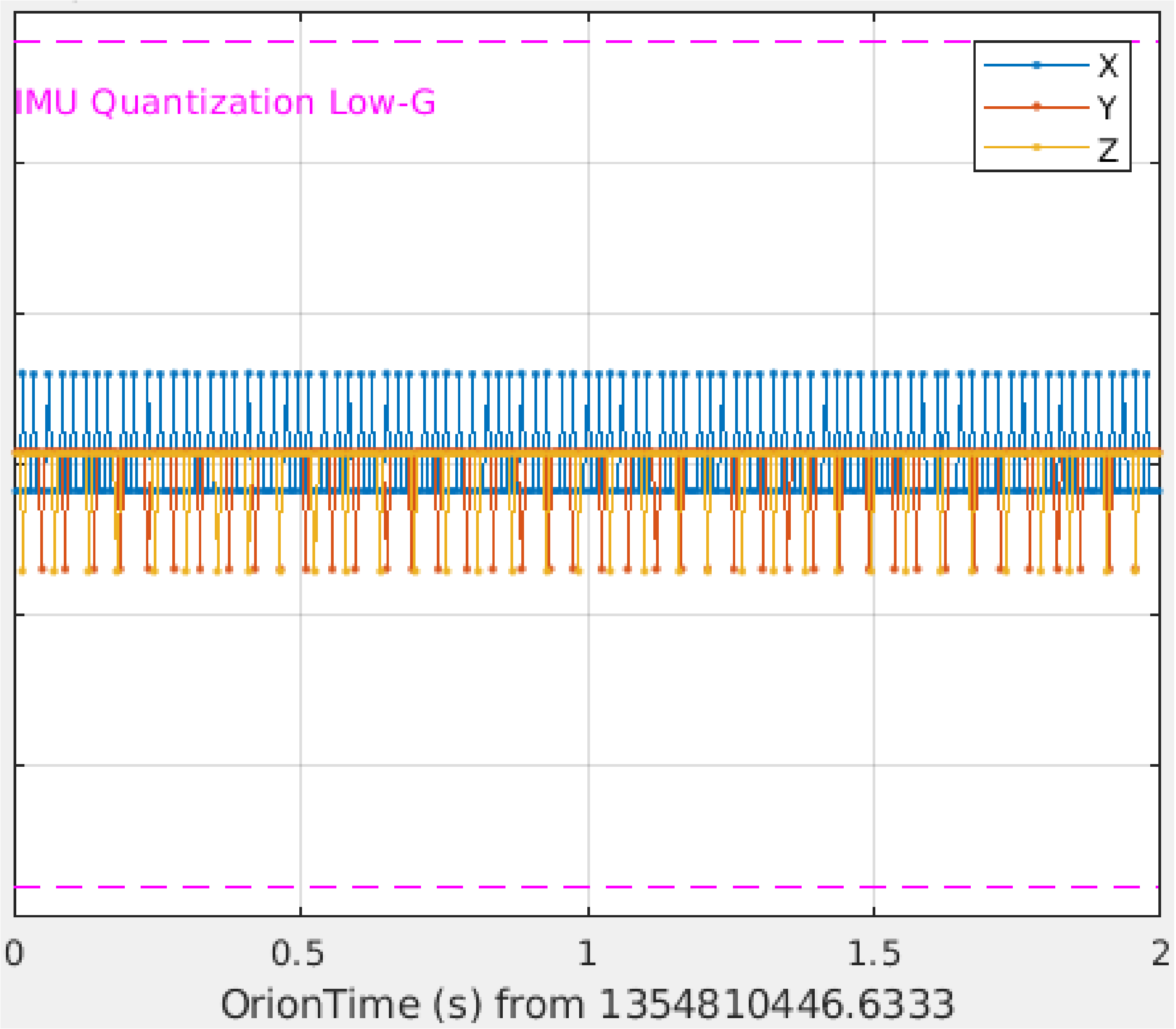
- **BET tool development started under assumption that time coherent data would be available**
  - Nominally in the future, data acquisition pipeline would result in a data history and a time history for any given CUI
- **Much work was spent developing pipelines to pre-process data**
  - NASA-side worked with raw Ops History files to decompress to formats readable by analysis tools
  - LM provides a data pipeline for lab test data
    - This pipeline was hacked to read in flight data, but work was done near real-time
  - Both pipelines worked to varying degrees of success
    - Final data product was a combination of both pipelines
    - Data chatter, data loss during DEM reconstruction, and data dropouts still present
- **Consequently, BET is generated from degraded data**
  - The primary data sources will be covered to illustrate this

ACCELEROMETER DATA

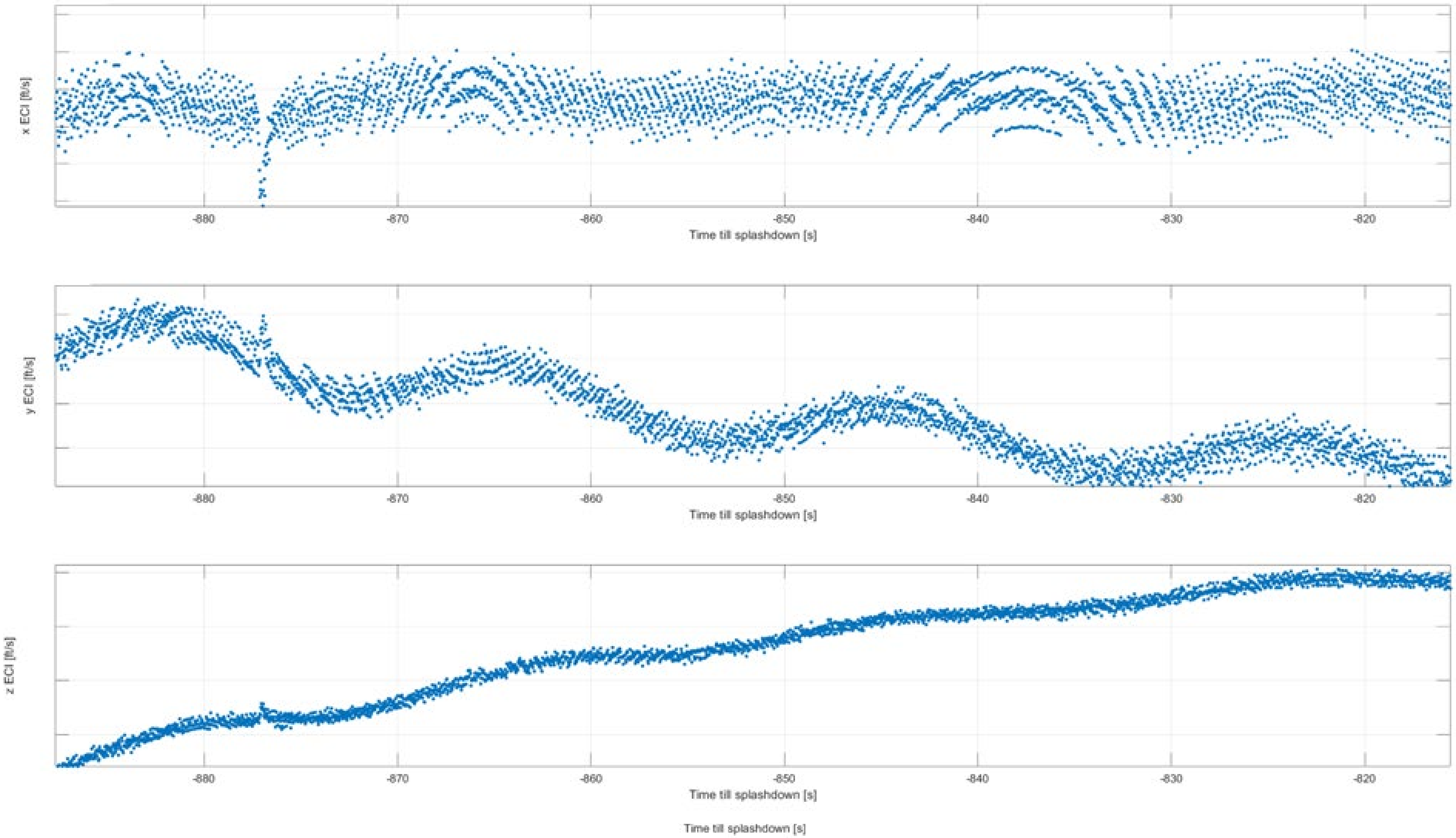
IMU Data

- **IMU data is recorded at 200 Hz on the vehicle**
  - Stored in a 6-element buffer due to 40 Hz flight computer cycle
- **Significant IMU data degradation due to time synchronization dependence**
  - Data chatter – data seems to be scrambled across time
  - Data loss due to lack of associated time tags
- **Fortunately, fault detection, isolation, and recovery (FIDR) signals were available**
  - Accelerations derived from IMU data logged at 40 Hz
  - Data comes with its own challenges
    - Accelerations mapped to the vehicle structural frame using a constant transformation
      - i.e. does not account for structural deformation due to vacuum-induced ballooning, G-forces
    - Dependent upon available attitude data to map into inertial frame

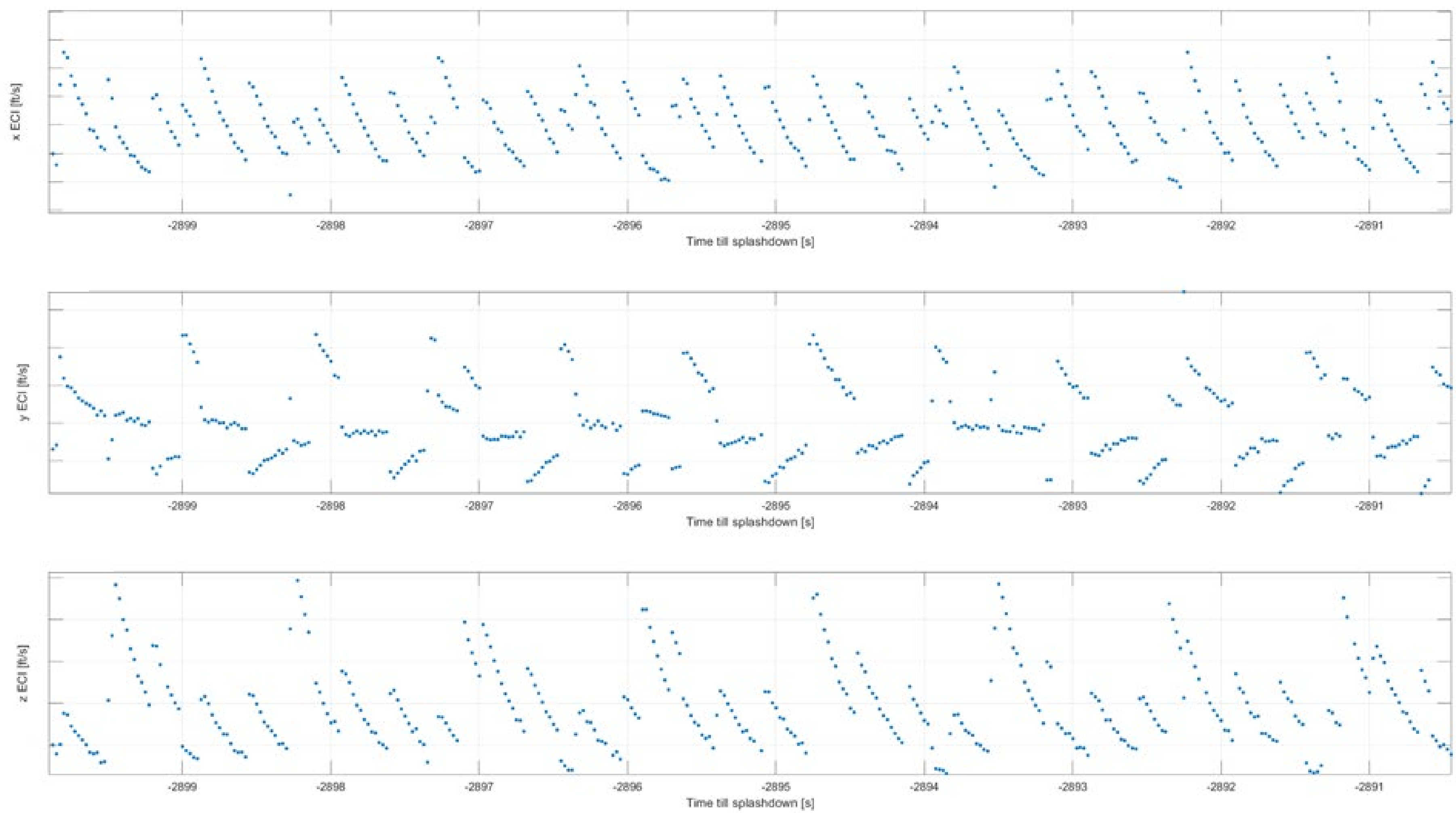
IMU Data


IMU Quantization Low-G
X
Y
Z
0
0.5
1
1.5
2
OrionTime (s) from 1354810446.6333

IMU Data


x ECI [ft/s]
-880
-870
-860
-850
-840
-830
-820
Time till splashdown [s]
y ECI [ft/s]
-880
-870
-860
-850
-840
-830
-820
Time till splashdown [s]
z ECI [ft/s]
-880
-870
-860
-850
-840
-830
-820
Time till splashdown [s]
Time till splashdown [s]

IMU Data


x ECI [ft/s]
-2899
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-2893
-2892
-2891
Time till splashdown [s]
y ECI [ft/s]
-2899
-2898
-2897
-2896
-2895
-2894
-2893
-2892
-2891
Time till splashdown [s]
z ECI [ft/s]
-2899
-2898
-2897
-2896
-2895
-2894
-2893
-2892
-2891
Time till splashdown [s]

IMU Data Summary

- **200 Hz IMU data was eventually recovered for entry**
  - Extracted directly from the recovered vehicle
  - Date of availability was too late to incorporate into these results
- **40 Hz data sufficient, but lowers BET fidelity**
  - At times, seems infeasible to assume post-flight solution outperforms on-board solution
- **Forward work is necessary for future missions**
  - Imperative to address issues exacerbated by buffering
  - Tools have been built in preparation for Artemis II
    - Time synchronization with interpolation
    - IIR filter to generate acceleration profile

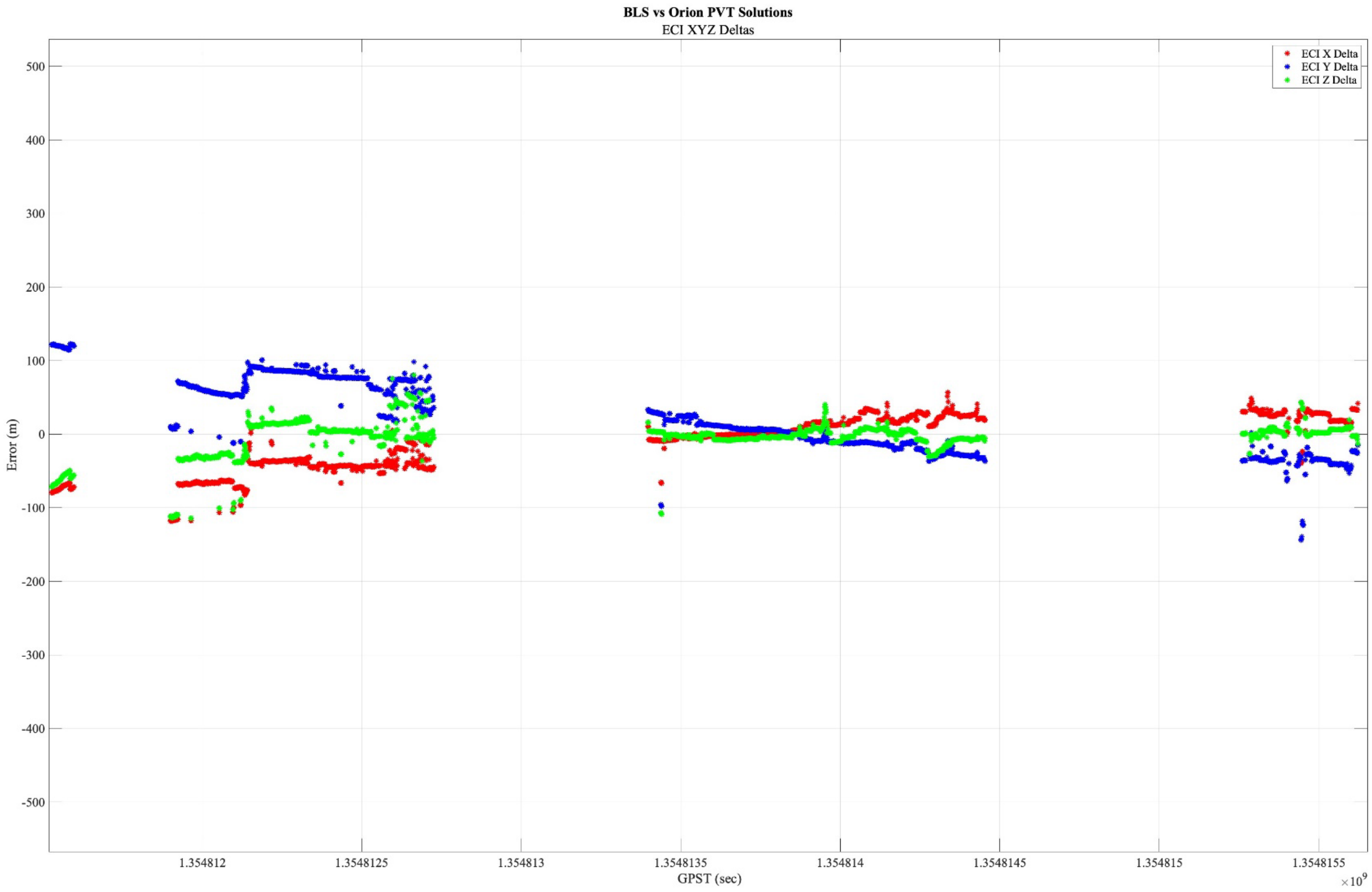
GPS DATA

GPS Data

Orion Project

- **GPS data nominally recorded in RINEX format**
  - RINEX is standard and useful in many OEM products
  - Pre-processing and segmentation beneficial for flight software
    - i.e. breaking GPS data apart from monolithic RINEX into individual signals
- **BET framework developed in FreeFlyer, requiring RINEX format**
  - Similar to IMUs, reconstructing DEMs is necessary
  - GPS data is also buffered to account for contact with multiple SVs
  - Consequently, similar but different issues
- **Tools were developed to reconstruct RINEX packets from flight data**
  - Some issues persist in telemetry
    - e.g. data and time tags stored in different packing maps, making their time synchronization impossible and resulting in data dropouts
  - As a result, verification is a crucial step in evaluating RINEX files
    - Independent batch least squares (BLS) estimates were generated to compare against GPSR PVT solution as a sanity check

GPSR BLS Results



GPS Data Summary

- **Issues unique to GPS data are minimal effort fixes**
  - Namely, ensuring time tags are stored in the same packing map as associated data
- **GPS possibly elevates BET to better-than-on-board solution**
  - Post-flight processing enables pruning of GPS data
    - e.g. a SV had bad health issues during entry, yet was still in comms with Orion
  - Loss of data due to time sync issues does raise some concerns
- **Regardless, same issues persist as IMU data, necessitating some solution for future missions**

ATTITUDE PROFILE

Attitude Profile Summary

- **Startrackers provide excellent attitude data when available**
  - Obviously this is not applicable during ascent and entry
  - The flight software had access to the full rate gyro data
    - In the absence of full rate gyro data on the ground, the on-board solution will be better
  - Similarly, flight software had access to a complete data set from the star trackers
    - This leads to a better attitude solution than can be achieved on the ground
- **Nominally, we could process all sensor data and estimate the full pose history of the vehicle**
  - Sadly, this is not the reality due to aforementioned data issues
  - As a result, in addition to the limitations of the COTS used to generate the BET, the attitude history from the vehicle is reconstructed for BET

GROUND OBSERVATION DATA

Ground Observation Summary

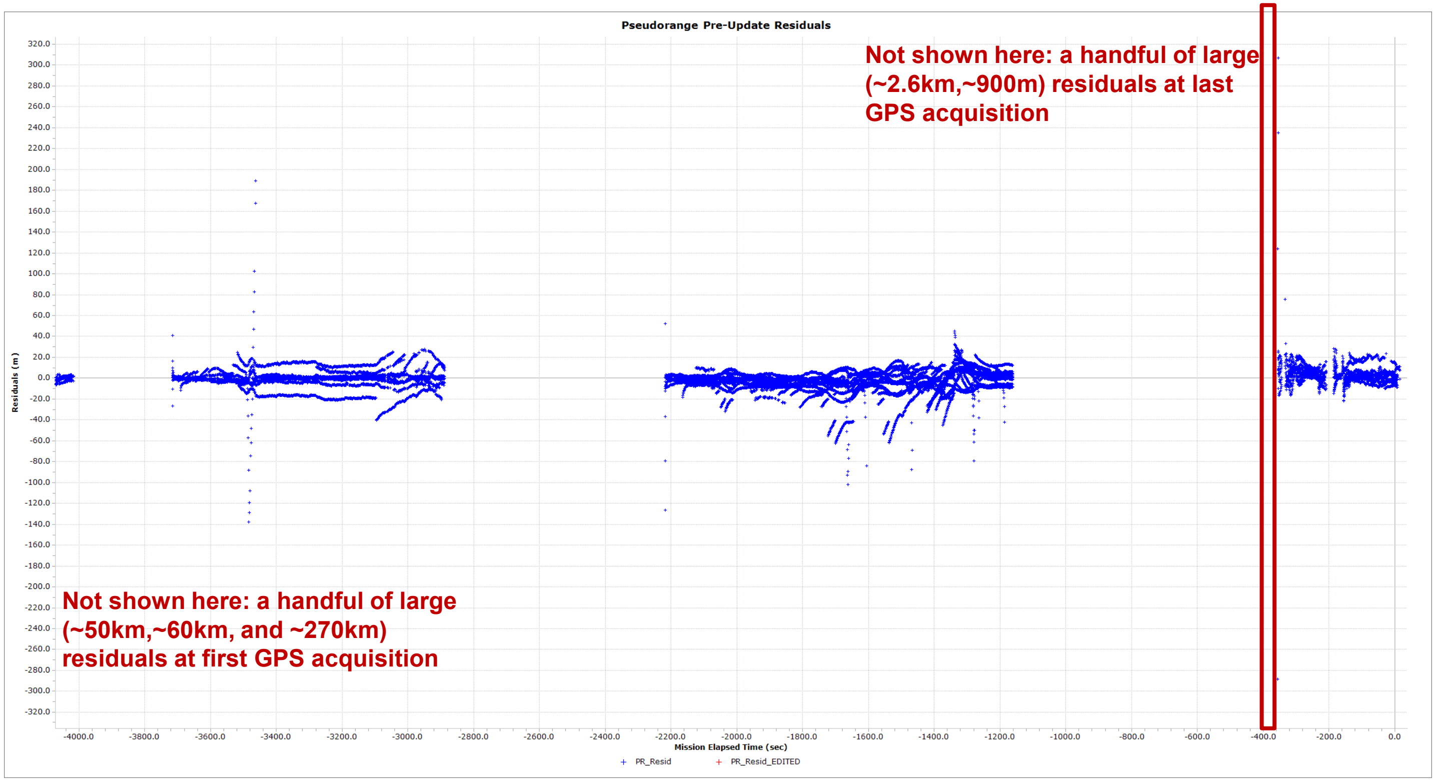
- **Radar data from the recovery ship as well as DSN data were recorded over the mission**
  - Time and resource constraints obviated these data from being used in generating the BET
  - The ground navigation systems had issues due to hardware hiccups and config issues
    - Ground navigation software were revisited to address these issues
    - A trade study has been performed and the results of said trade study will provide the orbit phase BET
      - In the future, it is paramount that solutions be developed to process (full rate) on-board data in addition to ground observations to generate the BET

BET GENERATION

BET Framework

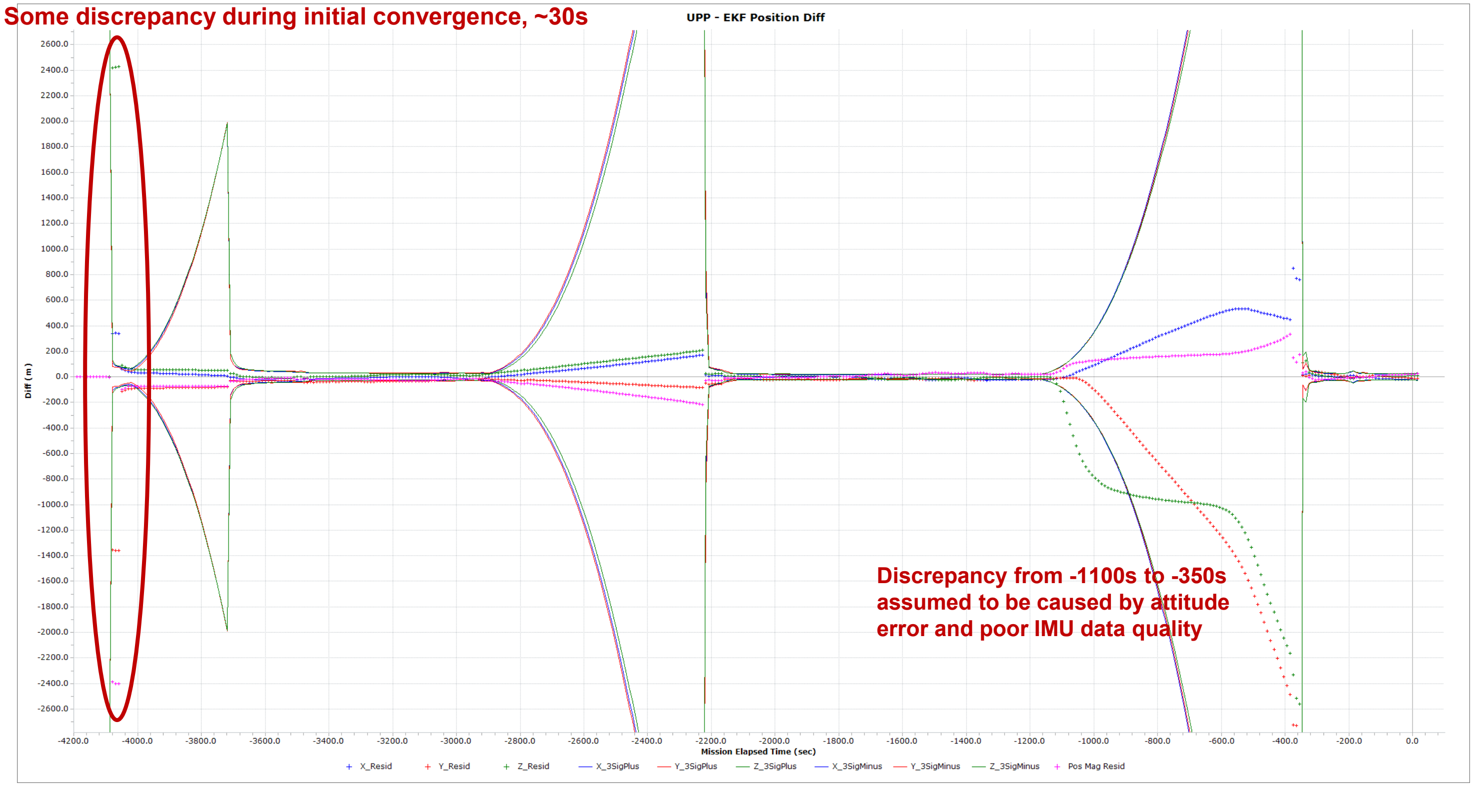
- **All work discussed to this point handles pre-processing BET data**
- **All available sensor data, as well as precise GPS ephemeris files, are then processed in FreeFlyer**
  - Attitude profile is provided as-is
  - Sensor data is processed in an extended Kalman filter (EKF)
    - Where applicable, estimable or noise parameters were initialized based on flight data
      - e.g. GPSR clock bias and drift, accelerometer read out noise, etc
  - To quantify performance, we observed
    - GPS pseudorange residuals
    - BET Position/Velocity as compared to on-board solution
    - Dynamic consistency
      - BET velocity vs. BET position rate-of-change ($v_k - \frac{r_k - r_{k-1}}{\Delta t}$)
      - IMU accels vs BET velocity rate-of-change sans gravitational accel ($a_k + g(r_k) - \frac{v_k - v_{k-1}}{\Delta t}$)

Pseudorange Measurement Residuals



- Pseudorange measurements at 1Hz rate
- GPSR1 acquisition: ~4100s prior to splashdown
- GPSR2 acquisition: ~2040s prior to splashdown
- All measurements passed the filter's residual editing check (5σ)
- For analysis and best wind estimates, final delivered product performed subsequent smoothing steps (not presented here)

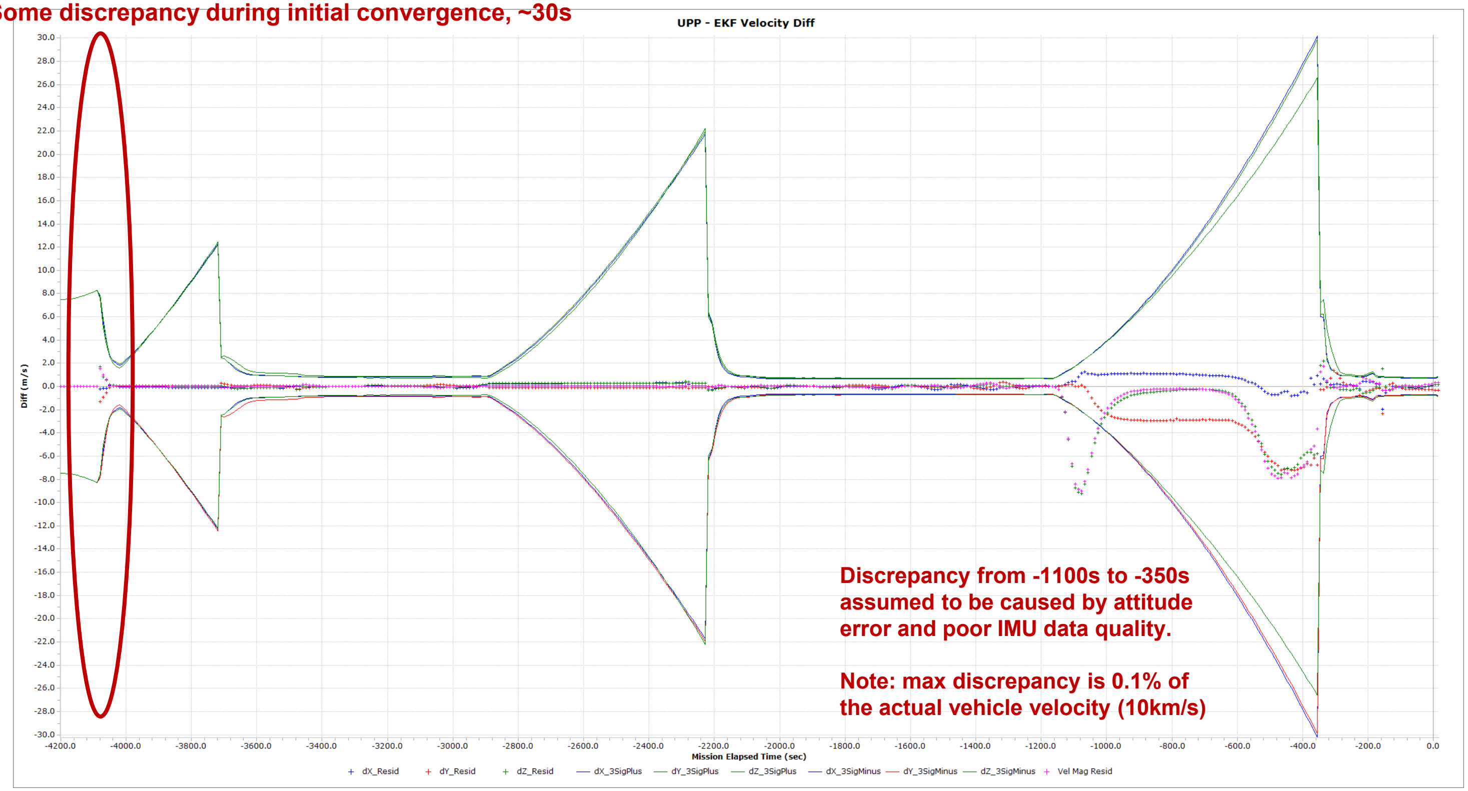
Filtering Results Position: UPPFast vs BET Solution



Filtering Results Velocity: UPPFast vs BET Solution

Orion Project

Some discrepancy during initial convergence, ~30s

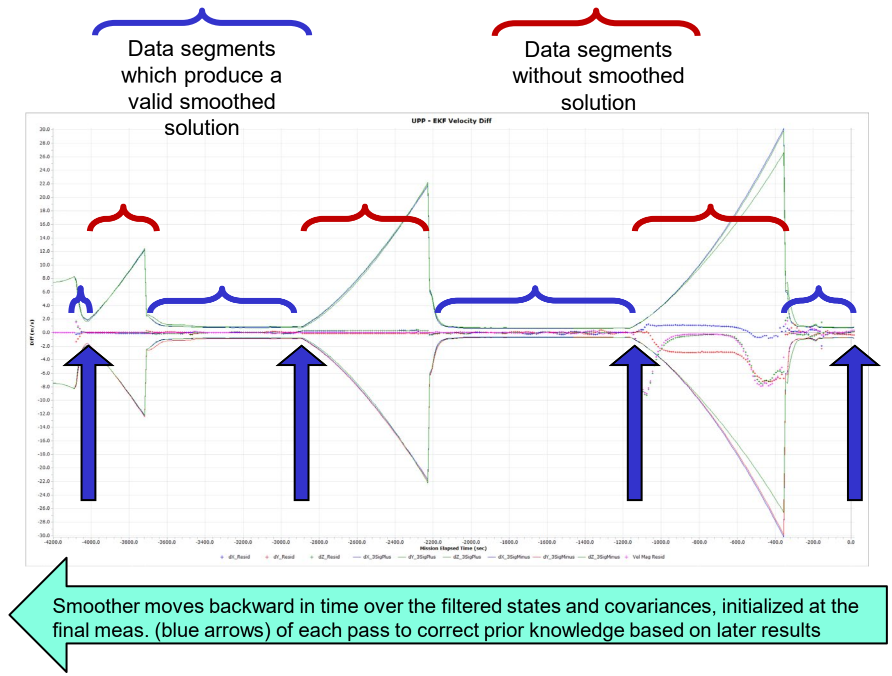


Discrepancy from -1100s to -350s assumed to be caused by attitude error and poor IMU data quality.

Note: max discrepancy is 0.1% of the actual vehicle velocity (10km/s)

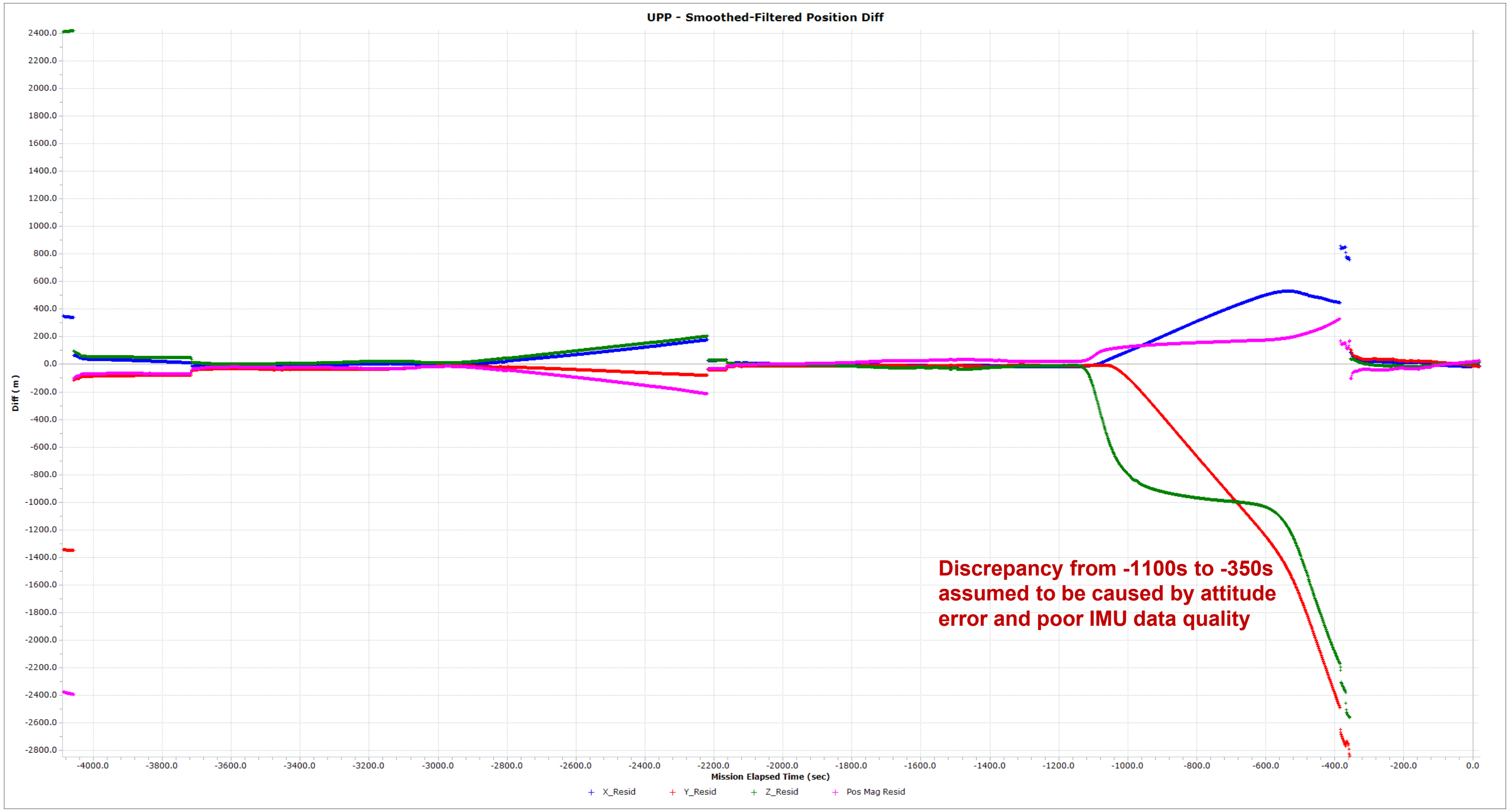
Rauch-Tung-Striebel Smoother

- **Fixed-lag RTS Smoother**
  - Inputs: forward filtered state and covariance history
  - Outputs: backward smoothed position and velocity states
- **Measurement data gaps**
  - The RTS smoother cannot appropriately handle the three large gaps (red curly braces, right) in GPS measurements
  - Smoother is instead initialized at the end of each measurement pass (blue arrows, right), and operates backward in time over each segment of measurement data (blue curly braces, right)
- **Smoothed result**
  - Smoothed position/velocity played back and recorded at fixed 40Hz
  - OIMU2 accels used to propagate the states between smoothed data points



UPP vs Smoothed 40Hz Output: Position Diff

Note: UPP ephemeris interpolated to fixed 40Hz points for evaluation using 10th order Lagrange interpolation



UPP vs Smoothed 40Hz Output: Velocity Diff

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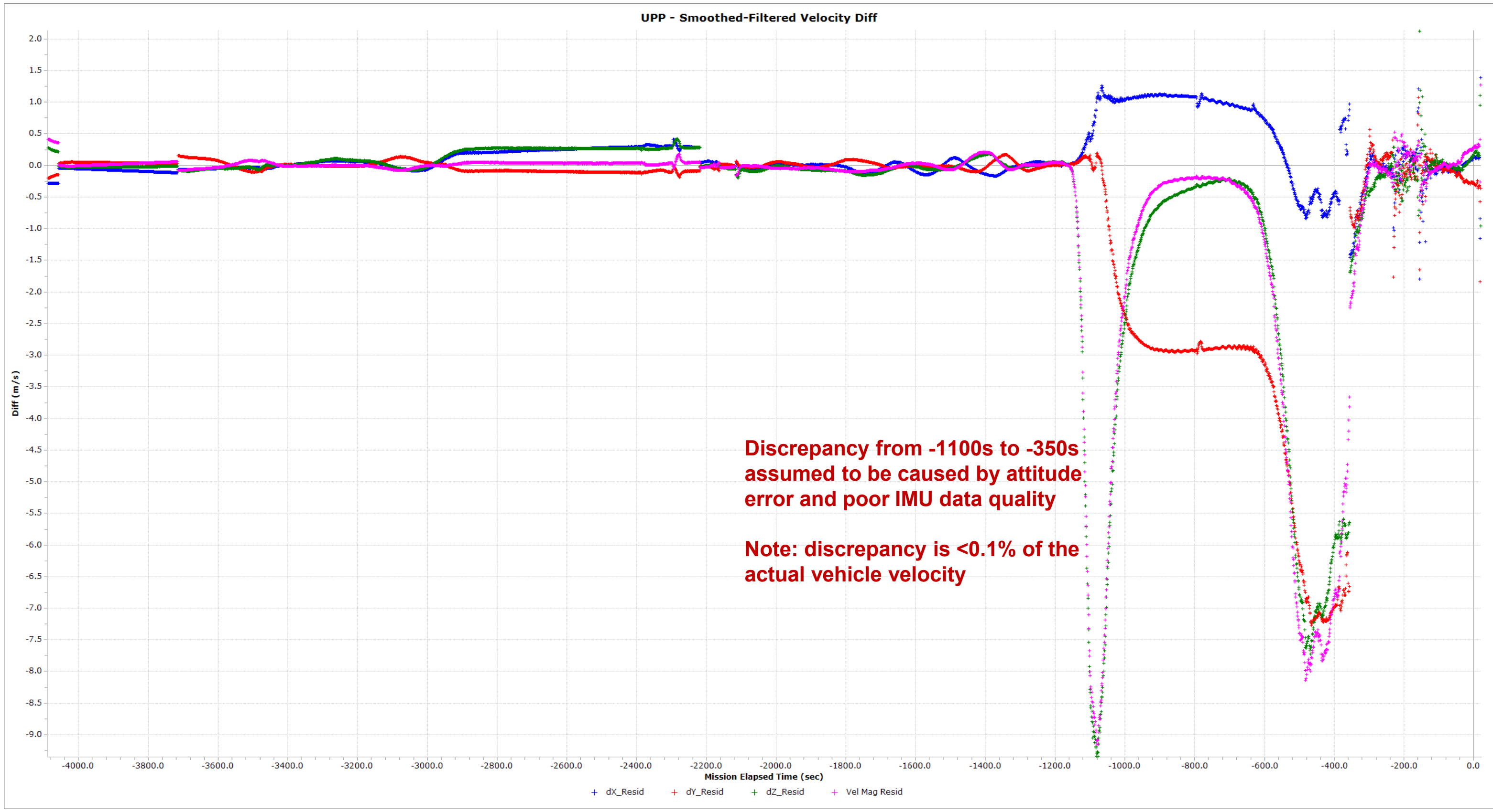
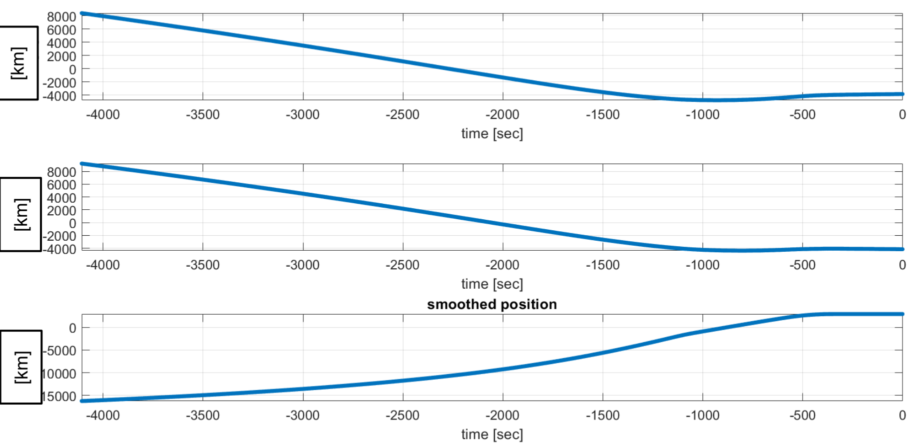


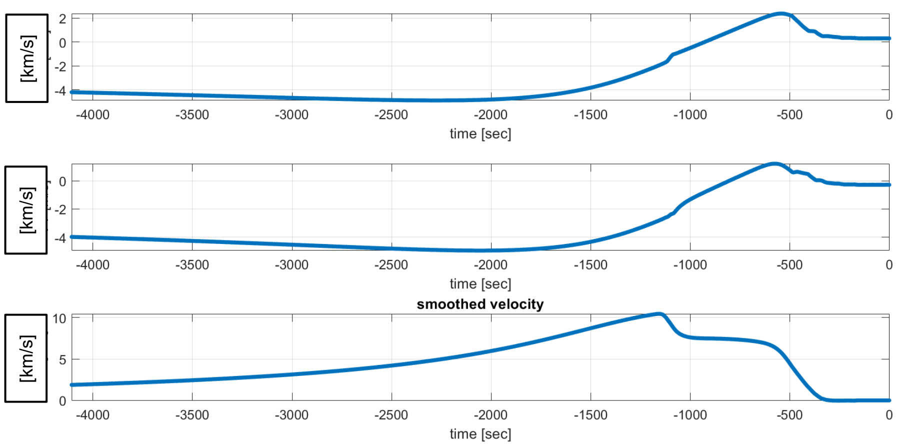
Output Data Quality

- **Output: fixed 40Hz ECI position and velocity**
  - RTS smoothed solution taken as truth at each measurement time (i.e. the times of the smoother output)
  - 40Hz synced inertial OIMU2 accels used to propagate the RTS smoothed solution to fixed 40Hz points
    - Large measurement gaps result in larger propagation errors

Position ECI



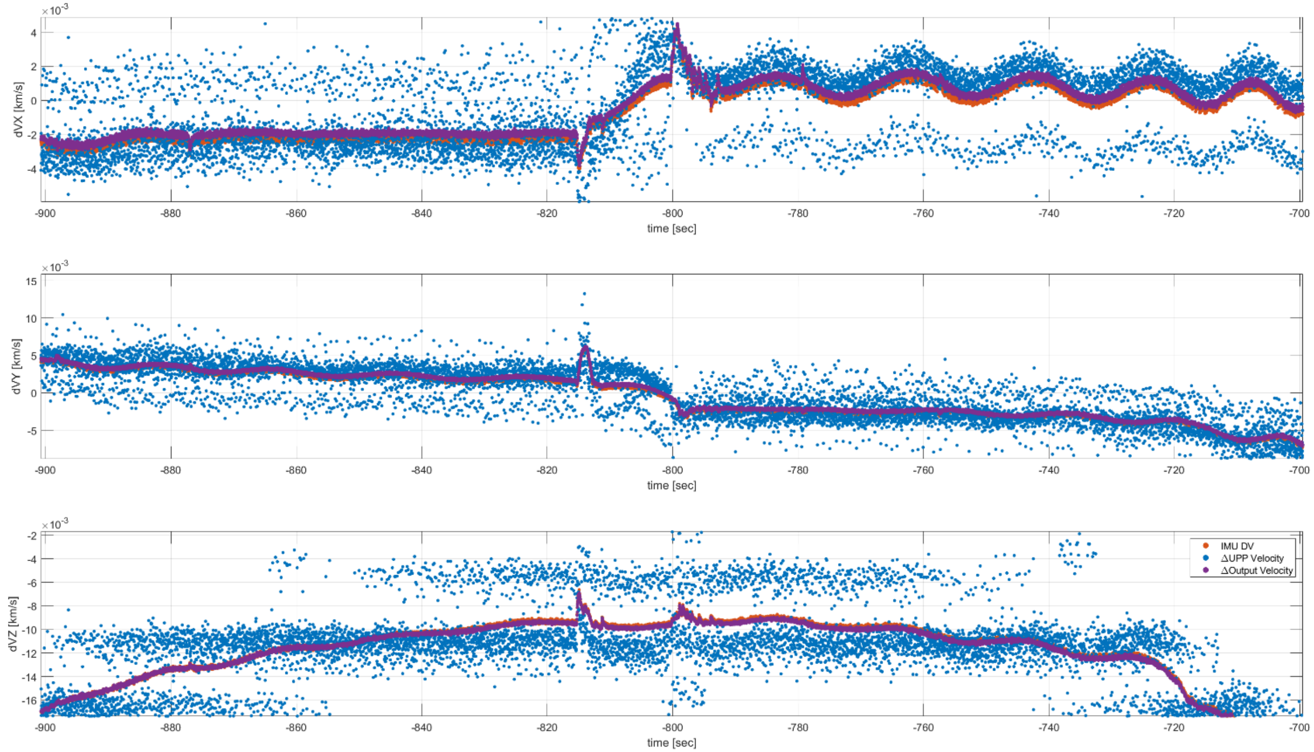
Velocity ECI



Derived non-gravitational ΔV at each timestep: UPP vs BET

Orion Project

Note: removal of gravitational ΔV from UPP and BET uses spherical gravity model



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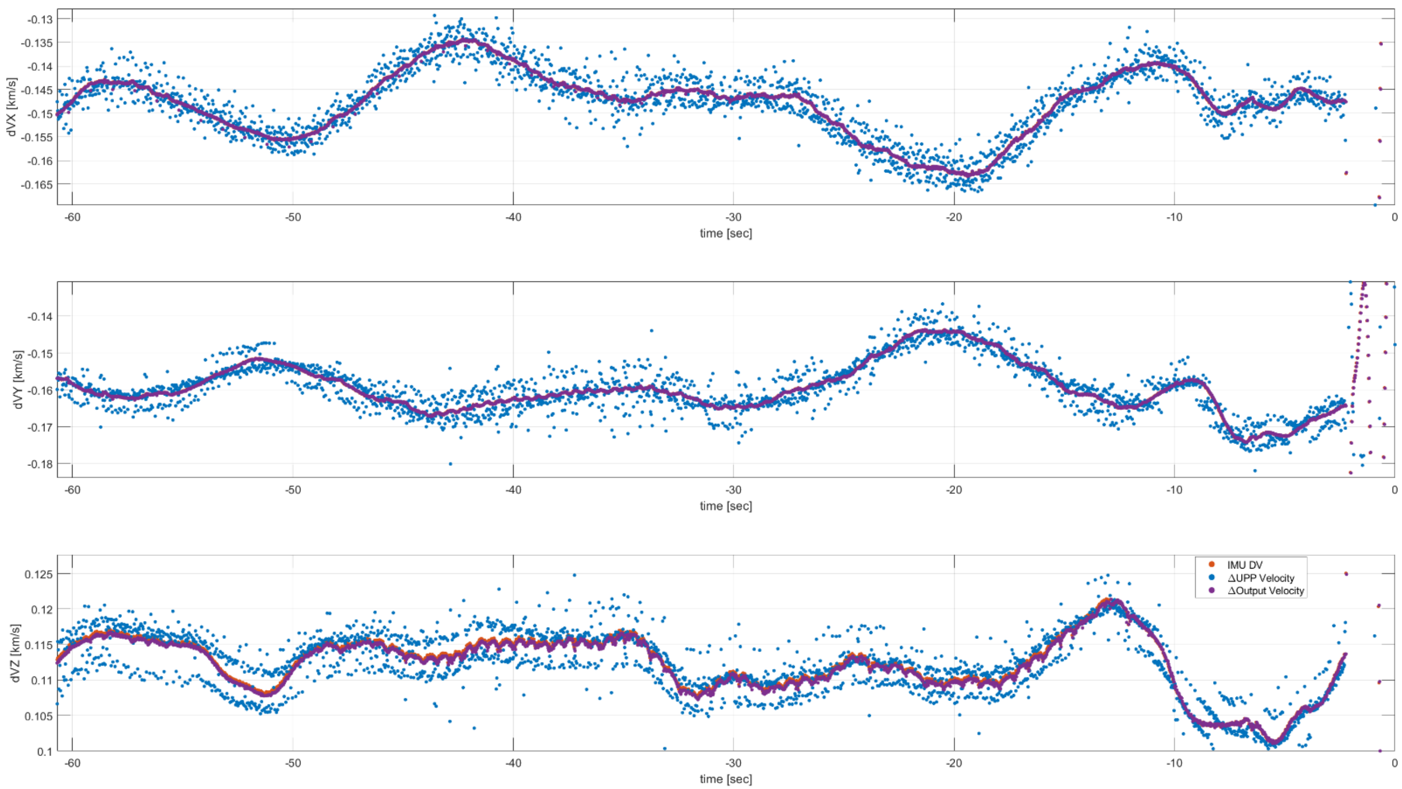
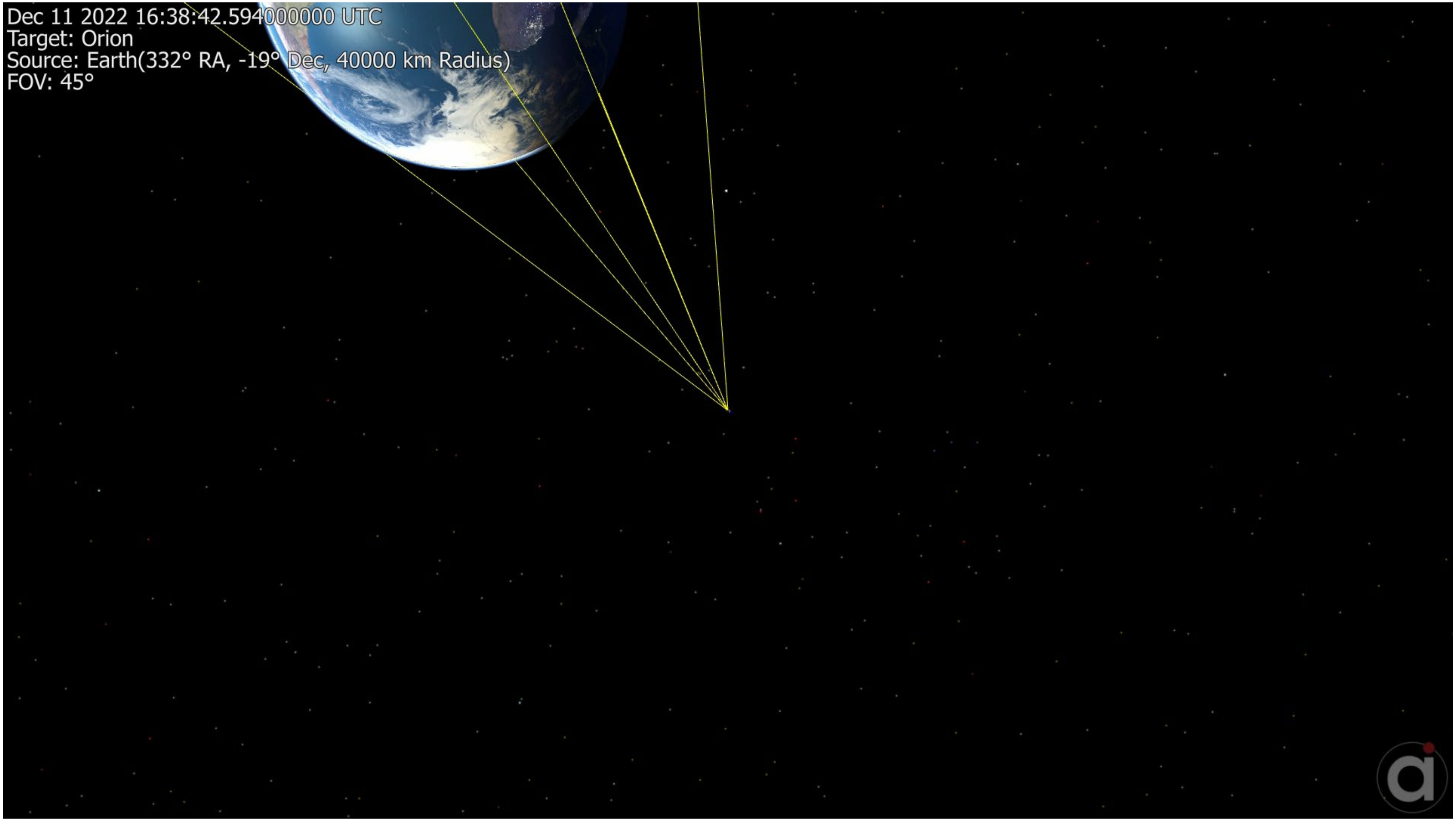


Entry BET


Dec 11 2022 16:38:42.594000000 UTC
Target: Orion
Source: Earth(332° RA, -19° Dec, 40000 km Radius)
FOV: 45°

CONCLUSIONS

Conclusions

- **The Artemis I mission proved invaluable in several categories**
  - In most instances, sufficient data availability to complete FTOs/DFTOs
  - Exposed several weaknesses in our tools and processes
    - Telemetry has already been reorganized in response to A-I experience
    - Regular data downlinks need to be scheduled and rigorously followed
    - Data pipelines need to be shored up
    - End-to-end simulations of data downlink, decommutation/decompression, and pre-processing need to be exercised prior to launch
      - The “end-to-end” pipeline was not fully apparent prior to A-1
      - Executing this in a simulation environment provides truth to evaluate data products against
- **Entry and orbit BETs have been generated and delivered**
  - Ascent is still a work in progress due to large data gaps

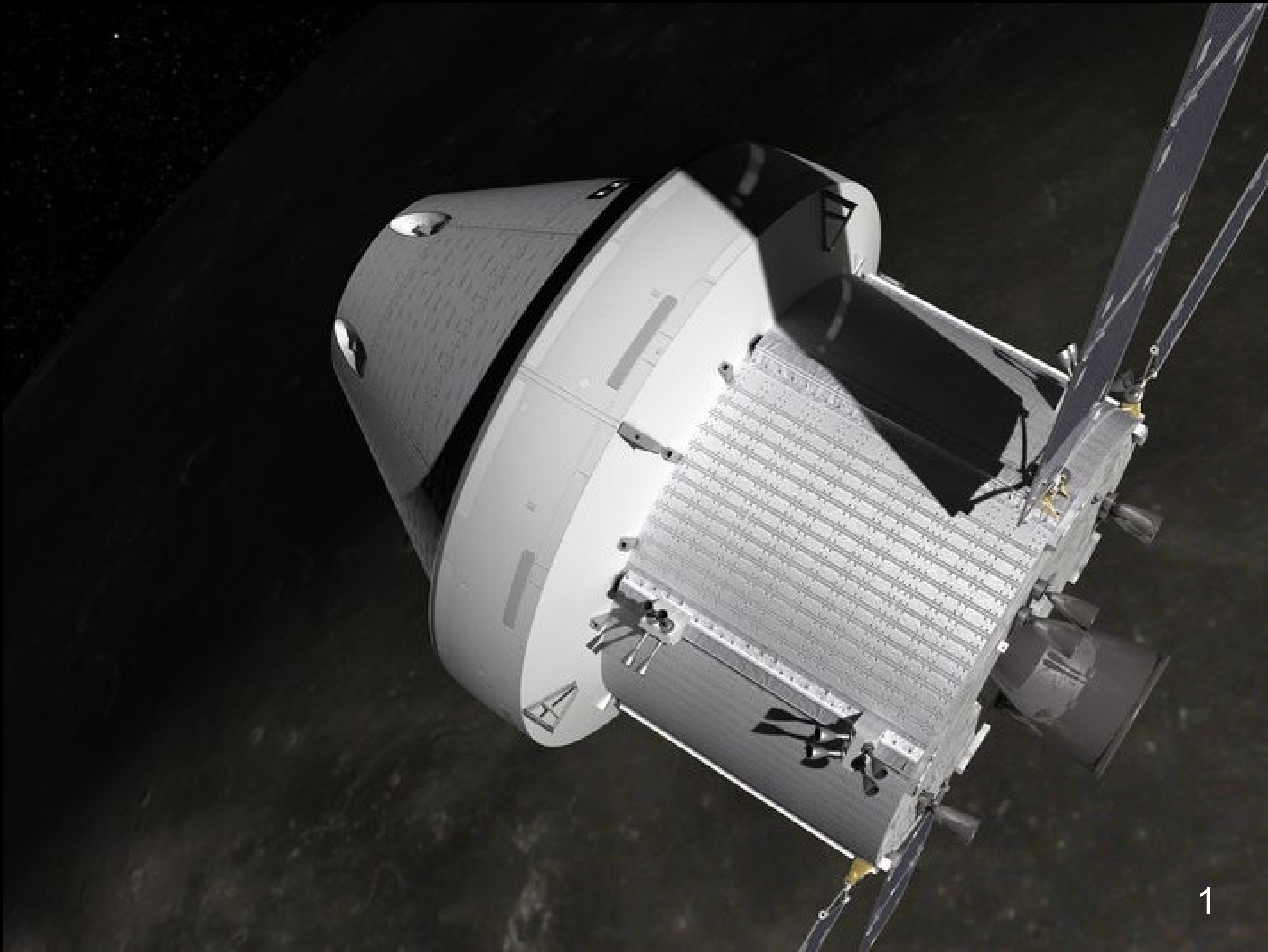
Conclusions

- **Entry and orbit BETs have been generated and delivered**
  - Ascent is still a work in progress due to large data gaps
  - Final effort of stitching together the three phases will need to be undertaken
- **Several tools were developed to handle data shortcomings**
  - Pre-processing and analysis tools available for ensuring clean BET data
- **Still, the BET framework was developed under less-than-ideal circumstances**
  - Extremely limited resources resulted in sporadic development
  - Late data deliveries coupled with short turnaround times resulted in hastily generated products
  - Most importantly, the framework was developed to handle imperfect data, with several stop-gap solutions incorporated

Conclusions

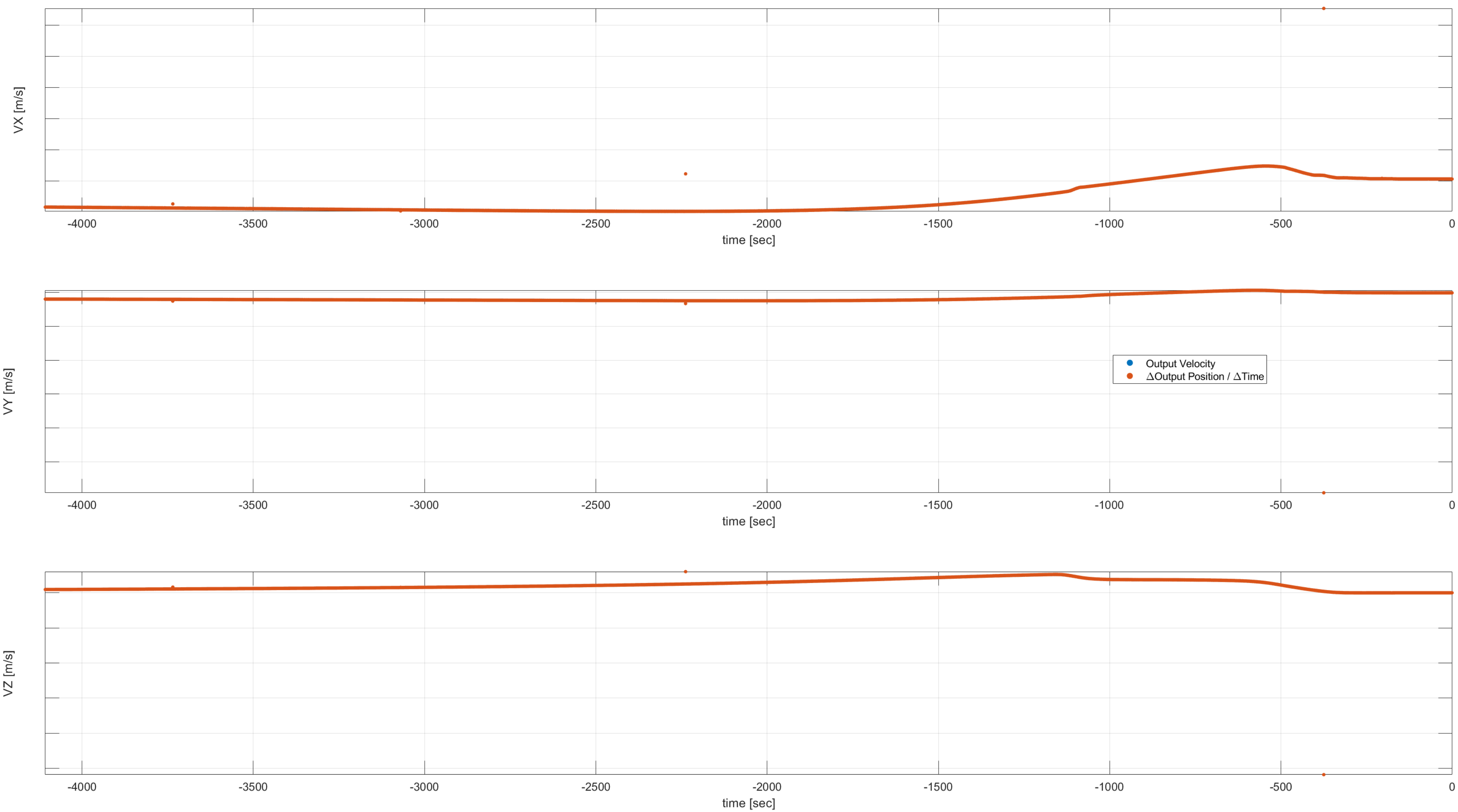
- **It is crucial we learn from these complications**
  - Dedicated teams need to be established for:
    - Telemetry and data recording systems (raw files on the system to the ground)
    - Data pipelines (decommutation/decompression and formatting of data)
    - BET team with more tangible resources

Backup



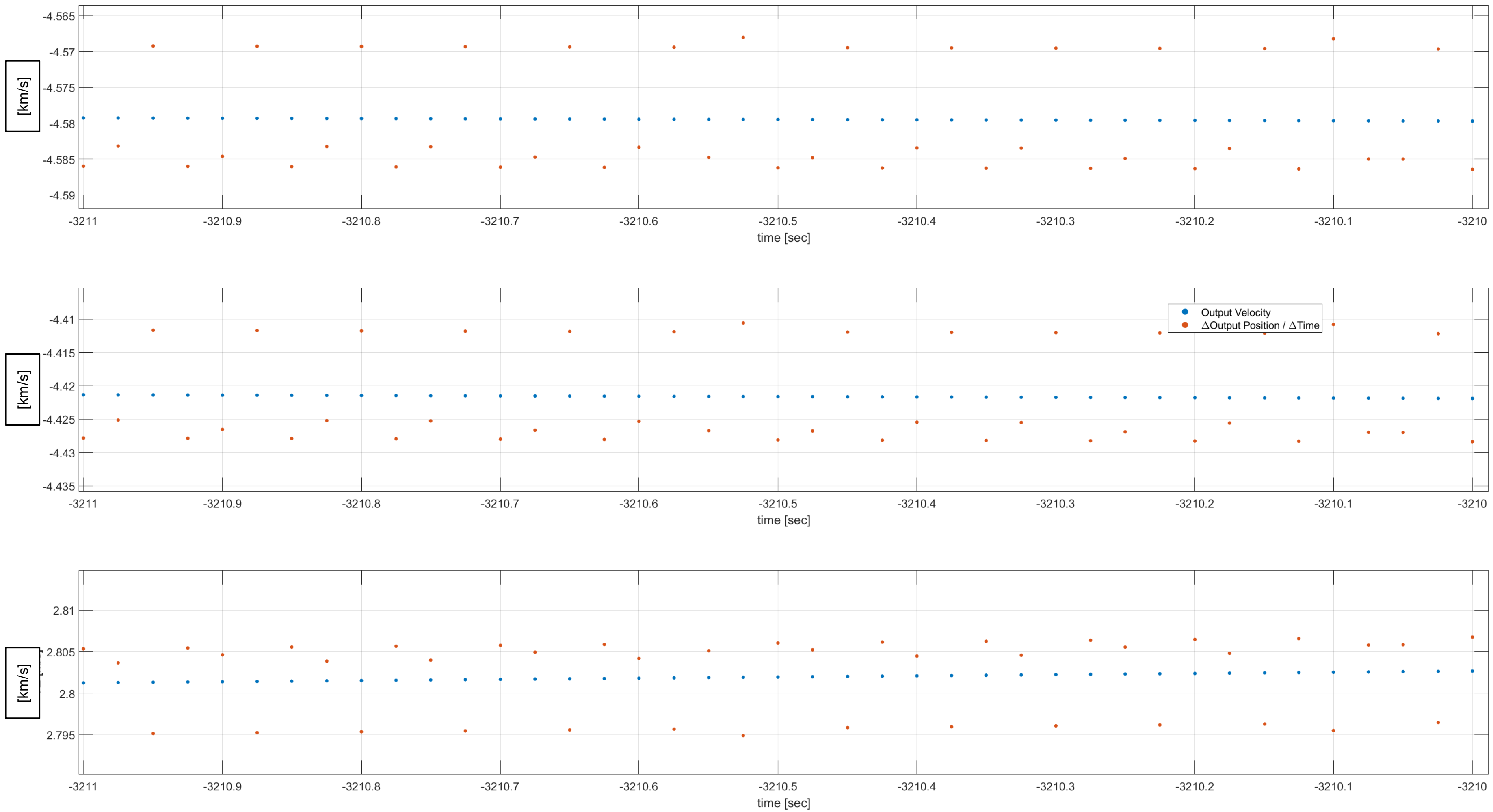
Velocity vs Position Rate of Change

Orion Project



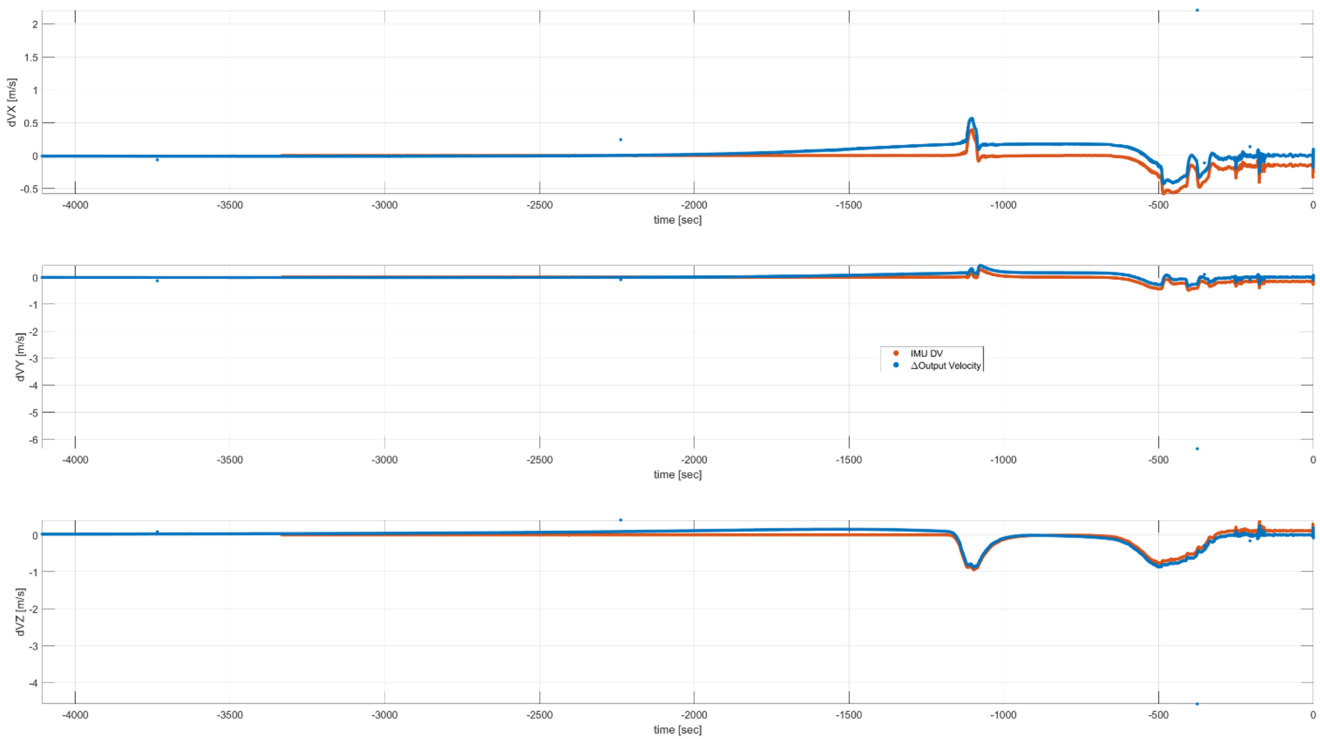
Velocity vs Position Rate of Change – 1s Interval

Orion Project



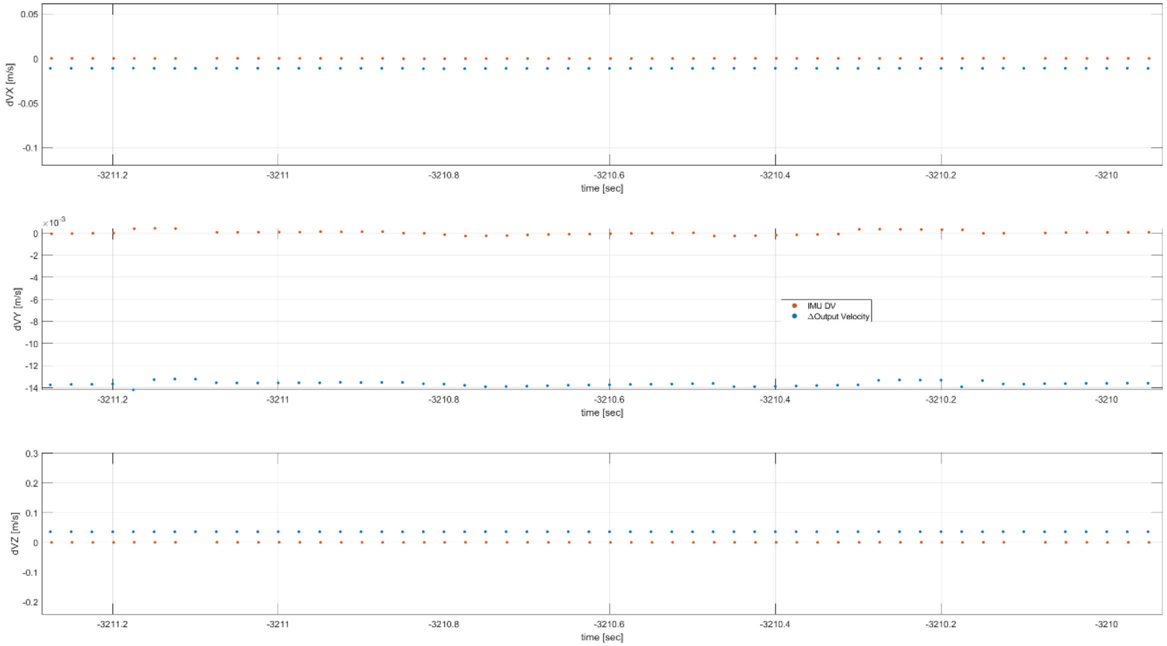
IMU DV vs ΔVelocity

Note: computed ΔVelocity includes changes from gravitational acceleration, IMU DV does not



IMU DV vs ΔVelocity 1sec Interval

Note: computed ΔVelocity includes changes from gravitational acceleration, IMU DV does not



IMU DV vs ΔVelocity 1sec Interval

Smoothed Δvelocity shown here includes correction for gravitational acceleration