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ORION ARTEMIS I (A-1) BEST ESTIMATED TRAJECTORY DEVELOPMENT

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The Artemis I mission launched on November 16, 2022 and concluded successfully on December 11. The purpose of this historic flight was to exercise the Space Launch System (SLS) and the Orion vehicle as a whole. In order to exhaustively evaluate not only the Orion system, but also the requirements and procedures in place for flying the vehicle, several flight test objectives (FTOs) and developmental flight test objectives (DFTOs) were performed to stress the system and collect data necessary for sufficient post-flight analysis. However, many of these analyses require some benchmark to evaluate against. This paper will detail the generation of this benchmark, the Best Estimated Trajectory (BET), through the forward filtering and backward smoothing of all the available flight data. Generation of the BET faces significant challenges, including parsing and pre-processing large amounts of flight data, incorporating ground measurements in the presence of both hardware and ground navigation software issues, and handling and filling in discontinuities due to data drop outs or new sensor data acquisition. This paper addresses these challenges as well as presents the end-to-end process of the A-1 BET reconstruction. Performance of the BET is presented for the entry phase to provide some objective data for the execution of the BET generation process.

INTRODUCTION

On November 16, 2022 at around 0640 UTC, NASA's Orion crew module (CM) began its maiden voyage atop the Space Launch System (SLS). Several correction burns and days later, the vehicle would eventually reach a near rectilinear halo orbit behind the moon. The mission concluded successfully when the CM re-entered the Earth's atmosphere and splashed down 25 days later on December 11. This flight was designed to be an exhaustive test of both the hardware and software systems in place to safely fly the vehicle, as well as the processes in place on the ground in Mission Control to support the mission. To achieve this, several tests were performed over the duration of the mission to gather data and get a more complete picture of the capabilities and characteristics of the system. Many of these tests are either directly related to guidance, navigation and control (GNC), or require GNC to provide a benchmark or a "truth" to evaluate against. While the on-board navigation solution provided during the mission was sufficient for real-time operations, a more accurate evaluation of the system in these flight tests is desirable to improve performance for subsequent Artemis missions. As the accuracy of this post-flight analysis is ultimately dependent on the accuracy of the GNC-furnished "truth," it is of interest to provide the most complete reconstruction of the trajectory possible, incorporating all available data sources and providing a statistical representation of the best understanding of the trajectory that the vehicle actually flew. This work documents the efforts that have gone into generating this best estimated trajectory (BET) and identifies some of the key issues that were uncovered in its generation.

The rest of this paper is organized as follows: the overall framework is outlined, followed by a discussion of the challenges faced in extracting and processing the vehicle flight data. The paper goes on to detail the generation of the attitude profile for the full duration of the mission, the construction of the external force

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file from the inertial measurement unit (IMU) data, the processing and validation of the GPS data, and the availability and end-result of the observations taken from the ground. These discussions attempt to outline the initial nominal design of the BET framework, while also capturing the additional efforts that were required as issues arose. Some data and results are subsequently presented, illustrating the evaluation that went into the IMU data to discern the best inertial acceleration source, the reconstruction and validation of the GPS data, and finally a comparison of the generated BET and the on-board navigation solution. Due to time constraints, resource limitations, and export control considerations, these performance metrics are limited to the entry phase of the mission. The paper closes out with some statements summarizing the BET effort, most notably the issues that persisted and impacted the effort and quality of the end-product.

LIMITATIONS

Several challenges and limitations presented themselves throughout the development of the BET, chief among them being data acquisition and processing. Data capture can be a difficult problem in any long duration mission due to the sheer quantity of data that is desired and the stringent bandwidth constraints to which data transmittal is held. Consequently, several techniques are used in recording and compressing the data to make the most of the bandwidth available. Decompression on the ground and subsequent pre-processing steps were thoroughly tested and in many instances revamped to address obstacles as they were discovered in real time. Many issues with the data recovery were resolved, however some are still being analyzed to gain a better understanding of their root cause. Unfortunately, one data source significantly impacted by these issues is the full rate 200 Hz Orion IMU (OIMU) data, an issue that was also experienced in generating the BET for the Experimental Flight Test 1 (EFT-1) [1]. This forced a filtered and downsampled 40 Hz OIMU data source to be used in the BET generation in its stead.

In addition to the difficulties of acquiring the data, the data that was acquired exhibited data dropouts in which data was not recoverable, as well as degraded data that negatively impacted the ground (and sometimes the on-board) navigation solution. Not to be confused with dropouts due to loss of communications, the former refers to portions of the flight in which the data files were simply lost or overwritten before they were downlinked. Degraded navigation data was observed at two different points during the mission and manifested in two different ways. During the start of the flight and through the second outbound trajectory correction maneuver (OTC-2), ground tracking range and doppler observations were captured by dishes on the deep space network (DSN). Initially, the dish hardware was configured incorrectly, leading to a bias that degraded the ground navigation solutions. Conversely, as the vehicle entered the lunar gravity well, the ground navigation software configuration led to an over-confident estimate result that also generated degraded navigation solutions. These issues were not anticipated in the early work on the BET framework, and consequently necessitated an alternative for generating a trajectory profile for the orbit phase of the mission.

The last challenge and limitation that will be highlighted in this work will be with regard to the OIMU mounting location and orientation within the vehicle. Due to design and budget constraints, the OIMUs were not placed on a rigid navigation bench nor were they all collocated; two of the three were placed near each other, but the third was placed in a disparate location. As a result, each OIMU has a unique transformation from their respective computational center reference frame to the Orion body (OB) frame. These transformations were derived from metrology data that was taken on the ground. Structural analysis posited, and thermal vacuum testing later confirmed, the pressure differential between the capsule's interior and exterior would result in some unmodeled flexing of the OIMU mounting orientations. Further analysis suggested that the acceleration forces experienced during ascent and entry would also have an affect on their orientations. Ideally, the influence of these unmodeled deflections should either be corrected for or characterized in the final BET product. However, due to data issues that will become prevalent in the following sections, these deflections were not characterized and instead a fixed transformation performed by the flight software was used in mapping the accelerations to the OB frame.

COORDINATE FRAME DEFINITIONS

The delivered BET product provides the flown trajectory in the international celestial reference frame (ICRF) [2] along with the attitude of the OB frame (a coordinate frame centered on the CM center of mass with the positive x-axis extending through the nose of the CM) relative to ICRF. However, the computational center of the OIMUs are what the GNC software navigates (referred to as the IMU computational center frame, or IMUCC), and consequently BET is inherently tied to the IMUCC coordinate frame. As mentioned in the previous section, the transformation from the IMUCC frame to the OB frame varies depending on the phase of flight of the mission and is not known perfectly. Any transformations for sensor-derived data (OIMU, star tracker, GPS) follow Orion spacecraft conventions [3].

BET GENERATION FRAMEWORK

Due to numerous factors such as the complexity of the data systems involved in storing and retrieving the flight data, the compression techniques employed, and the structure of the telemetry and on-board data recorder, several steps are involved in generating the BET. An overview of the current work flow can be seen in Figure (1). The Orion block identifies all of the on-board data sources that will be used directly in generated the final reconstructed trajectory, and the DSN currently represents all of the external observation sources. The rest of the diagram illustrates the complexity of the full life cycle of the data as it transits from the data source to the analysis tools.

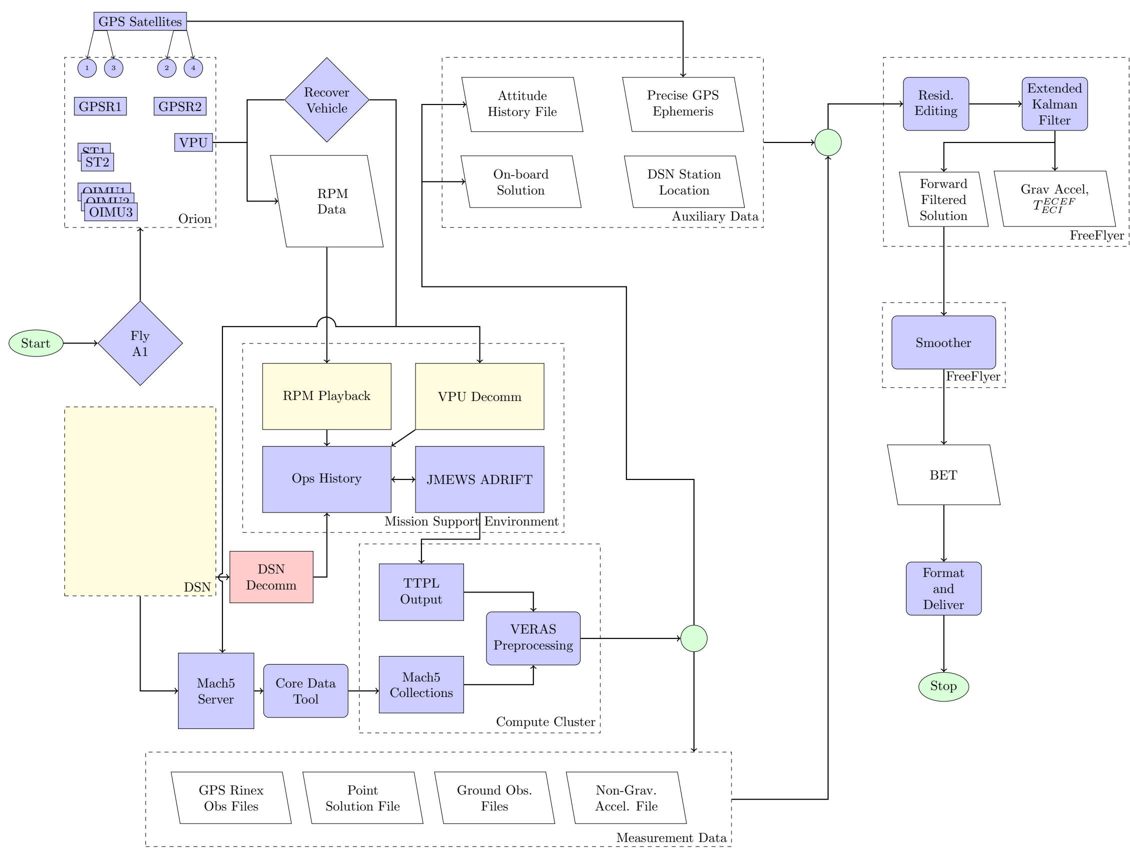

Figure 1. A high-level overview of the ascent and entry BET framework, from data generation through filtering and smoothing.

Some elaboration is warranted to follow the flow chart in Figure (1). The Orion block shows the primary sensors leveraged in the BET generation, namely the GPS receivers (GPSRs) and their associated antennae (circles 1-4, top of the Orion block), both star trackers (STs), the three OIMUs, and the vehicle processing unit (VPU) block denotes the flight computers and data recorders used to record or telemeter the data. Telemetered data is received by the DSN and is both decommutated into the ops history server, as well as extracted to the Mach5 data server, illustrated by the DSN block below the start of the flow diagram. In addition to the telemetered data, higher rate data is continuously captured and stored in recorded packing maps (RPMs) which are downlinked periodically throughout the mission with the exception of the final roughly 24 hours of data, which is extracted from the vehicle upon recovery. The telemetered data, downlinked data, and data extracted from the vehicle are accessible through two independent data pipelines that are detailed further in the following section. These pipelines, along with the VERAS (Verification, Evaluation of Requirements, Analysis, and Synthesis) Python software suite, enable the necessary pre-processing of all of the auxilliary data and the measurement data to be performed before being fed into the FreeFlyer BET framework. Finally, the repackaged data is run through a forward filter and backward smoother in FreeFlyer to generate the final BET. This completes the nominal end-to-end process of receiving flight data to generating a BET; however, in the current implementation the ground observation has not been processed in FreeFlyer and is instead being processed separately in a different tool as time and resource constraints prevented the FreeFlyer version from being completed. Additionaly, it is important to note that some of these data sources, namely the On-board Solution (i.e. the time history of the navigation solution that was generated on-board the vehilce) and the Point Solution File, are used exclusively for initialization points or for performance quantification, and were not processed in the filter as they are products derived from the other measurement sources feeding the BET.

Due to this complexity of this pipeline, documentation describing the BET effort without discussing in greater detail the front-loaded work required in pulling and pre-processing the flight data would be incomplete. The following sections provide further detail on the different stages depicted in Figure (1), along with the solutions required to progress through each step.

ON-BOARD SENSOR DATA ACQUISITION AND PRE-PROCESSING

On-board the Orion vehicle, three OIMUs propagate three independent navigation solutions (or channels) for the entirety of the mission [4]. The propagated translational states are updated leveraging information from at least one (depending on the navigation channel) of the two on-board GPS receivers during entry, Earth orbit, and the portion of ascent when the GPS antenna are not occluded by the launch abort system (LAS); i.e. after the LAS is jettisoned. The GPS data also has a small impact on the rotational states in the navigation solution, but the attitude estimate is primarily driven by measurements from at least one (depending on the navigation channel) of the two star trackers. These sensors are the primary on-board sources of data processed in the navigation filters, and will also be utilized in generating the BET. In addition to these data sources, three additional sensors generated observation data: the Optical Navigation Camera (OpNav) [5, 6] an experimental sensor flown to certify its use in future missions, the barometric altimeters provided an alternative altitude source during entry, and the sun sensor provided the vehicle situational awareness for different solar pointing constraints. Due to program constraints and the dilemmas caused by the data extraction pipeline, these data are omitted from the BET and instead are to be independently evaluated against the BET in external post-flight analysis efforts.

Each of these sensors generated data that was either telemetered in real-time or recorded on the vehicle. This recorded data was then either downlinked during the mission or, in the case of the entry data, extracted from the physical vehicle processing unit (VPU) upon recovery of the vehicle. Depending on whether the data was telemetered, downlinked, or read directly from the VPU, the data was processed through different means, but eventually made its way to two independent data servers: the NASA-owned Ops History server and the Lockheed Martin-owned Mach5 server. Each of these servers afford a different data storage format, and consequently the two require their own unique data processing pipeline; perhaps unsurprisingly, the two exhibit a different set of challenges and issues. As a result, it was frequently necessary to pull and process data from both pipelines and merge the two data sources to get a more complete picture of a particular time frame of the flight.

Regardless of the data storage system of origin, additional pre-processing steps must be taken to ensure that the data are readily indigestible by the BET framework. Some of these pre-processing steps are universal to every datum to be processed, such as ensuring the time stamp associated with each sample is precise and represented in the Orion Time time frame. Other steps are specific to the sensor in question. These steps are, to the extent possible, detailed in the following subsections.

Orion Time Synchronization

Due to the complexity of the telemetry and data recorder systems, the constraints brought up by finite bandwidth limitations, and the varying methods of decompressing/decommutating data, several different time frames exist within the data. At the simplest level, data are grouped into different discrete packages such that when a single sample of that package is taken, all of the pieces of data belonging to that discrete package are placed into a single message referred to as a digital exchange message (DEM). These DEMs are constructed at the flight computer level and consequently are given a time stamp by the flight computer when a DEM is constructed. This time stamp, referred to as the DEM time, is also tuned at the sub-microsecond level to be used as a unique identifier such that when data are extracted from multiple DEMs, data belonging to a common DEM can be re-associated by matching their DEM times [7]. This factor becomes crucial when precise timing is necessary, such as in processing sensitive and/or high rate data.

DEMs are constructed at 40 Hz, and since data must be generated by the flight software and travel to the point at which it is packaged into the DEM, the DEM time stamp can feasibly lag the actual generation of the data sample by nearly a single 40 Hz cycle. Single measurement latency aside, some measurements aboard Orion are buffered and require time tags to be buffered alongside them, such as the OIMU measurements that are recorded at 200 Hz and buffered down to 40 Hz using a 6 element buffer. In order to guarantee the time tags and the actual sensor measurements are associated correctly, the uniqueness of the DEM times is crucial.

To complicate matters, in an effort to reduce the overall size of the raw files stored on the vehicle for downlink (or post-recovery extraction), data is compressed such that it is recorded on a change-only basis. The aforementioned VERAS software suite provides the capability to quickly associate data belonging to a common DEM by matching DEM times across samples, enabling the time tags recorded in flight software to be associated with (and subsequently applied to) other data such as the OIMU sensed accelerations in a process referred to herein as time synchronization (as it "synchronizes" the data with a different time framee). However, some phenomena have been observed in the time synchronized flight data such as frequent losses of data packets due to a lack of recorded time tags (e.g. a measurement with a specific DEM time does not have an associated Orion Time time tag with a common DEM time) or "data chatter" that presents as a scrambled data set, often appearing as multiple signatures overlayed on top of one another. This may be a result of the data compression used in the telemetry and data recording systems, although the behavior does seem to be limited to data that was telemetered or downlinked during the mission rather than the data extracted from the physical VPU. More analysis and work is required to fully address the problem for Artemis II.

Attitude Profile Generation

Due to its ability to natively handle TRK-2-34 data from the DSN [8], it was decided early on that the BET framework would be handled by the commercial-off-the-shelf product FreeFlyer [9], a mission analysis, design, and operation software application already employed by NASA to support several programs, including the ISS. One of the trade-offs of using FreeFlyer in the BET framework is the lack of an online attitude estimator that can run in parallel with the translational estimation. For much of the mission this is moot, as the precision and accuracy of the star trackers are such that the attitude state is very well characterized. Consequently, the on-board attitude solution maintained throughout the mission was used to generate an attitude profile for the FreeFlyer framework.

External Force File Generation

All translational burns throughout the mission will be modeled via the sensed accelerations in the OIMU measurements. This modeling manifests, in a FreeFlyer framework, as an external force file that defines the accelerations for the propagator in the software. However, these sensed accelerations cannot be used directly in the BET framework for a few reasons. The OIMUs are displaced from the center of mass of the vehicle, meaning there is a lever arm affect present that must be accounted for in the sensed accelerations. The transformation from the IMUCC frame to the OB frame is not constant, as it is a function of the pressure differential across the CM as well as the G forces experienced by the CM. And lastly, as mentioned in the time synchronization discussion, the measurements are buffered alongside their time tags recorded in the Orion Data Network (ODN) time frame. In generating an external force file that can accurately propagate Orion, these buffers need to be unwrapped and appropriately time synchronized, their times converted to the Orion Time time frame, the lever arm affect removed from the sensed accelerations, the sensed accelerations mapped into the OB frame, and then subsequently mapped to ICRF.

As mentioned in the Limitations and Orion Time Synchronization sections, the full rate 200 Hz OIMU data were significantly impacted by the data pipelines for the entirety of the mission prior to entry. When unwrapped and synchronized, the accelerations exhibited a significant amount of data chatter, as well as some notable data gaps which have been deemed non-recoverable. Fortunately, the on-board flight software performs fault detection, isolation, and recovery (FDIR) on the OIMU data before they are used to propagate a navigation channel. In order to perform these FDIR checks in a common frame to better compare measurements from all three OIMUs, 40 Hz signals are generated by running the 200 Hz data for a given OIMU through an infinite impulse response (IIR) filter to generate a 40 Hz acceleration signal in the Orion Body frame. This downsampled 40 Hz acceleration was used in place of the full rate data for the other phases of flight out of necessity. It is important to note that this data is still not immune to data dropouts; not only are there dropouts present in the OIMU data, but since the data must be rotated into the ICRF frame to be processed in FreeFlyer, the OIMU data viability is also compromised in the presence of attitude data dropouts.

GPS RINEX File Reconstruction

The overall hierarchy of the flight software breaks the software up into individual components referred to as computational software units (CSUs). The way these CSUs are packaged, as well as how FDIR is handled onboard the vehicle, greatly influences how data is transmitted between CSUs. As a result, the data delivered by the GPS receivers is repackaged into a more compact and intuitive structure, but in doing so the raw format of the GPS packets is lost and the ability to easily convert the raw data into a receiver independent exchange (RINEX) formatted file is also affected. Repackaging the GPS data in a RINEX format and accounting for the health and status signals provided by both the receiver itself and the onboard FDIR software is necessary in order to process the data in the filter and smoother.

Due to the complexities mentioned in the Orion Time Synchronization section, it is imperative to assess the quality of the data files as they are generated. In the case of the IMU data, this is as easy as plotting the measurements and checking them against some expected event times, e.g. is there a sensed acceleration at burn times, does splashdown occur at the right time. For the GPS data, the task is not as trivial. Considering this is the most information-rich data source during ascent and entry, extra care is taken to ensure that the resulting RINEX observation files are accurate. This validation is discussed in the following subsections.

Solving for GPS Receiver Position. Solving for GPS receiver position is fairly straight-forward. The solution at any specific time can be solved using a deterministic estimator, such as batch least squares (BLS), or can be solved in a sequential manner using an extended Kalman filter (EKF).

In either case, two pieces of data, collected at the same time, are required. First, the estimator must have at least four pseudoranges (further explained in the next section), and second, the accurate positions of the satellites that are providing the pseudoranges. From these two pieces of data, the estimator can calculate the earth-centered earth-fixed (ECEF) position of the receiver, and then can easily convert these to latitude, longitude, and altitude (LLA). In doing this and comparing the results against the mission timeline, these independent analyses can be used to verify that the GPS RINEX observation file has been reconstructed appropriately, with some data loss due to time synchronization (and data drop out) issues.

The GPS Pseudorange Equation. A pseudorange (PR) represents the range from the GPS satellite to the GPS receiver. The term ”pseudo” refers to the fact that the measurement is not the true range, but rather the range from the satellite vehicle (SV) at the transmit time t_{tx} to the receiver at the received time t_{rx}, where

$t_{tx} < t_{rx}$, corrupted with other errors (e.g. transmitter and receiver clock biases). These errors must be removed as part of the estimation process.

GPS pseudoranges are modeled using an equation that is comprised of the true range, ρ, plus a number of additional biases and error sources. The full model can be expressed as

$$PR = \rho + c(dt_{RX} - dt^{SV}) + T + \alpha_t STEC + dp + K_{P,R} - K_P^S + M_P + \epsilon_P$$

where

$$\begin{aligned} PR &= \text{pseudorange} \\ \rho &= \text{true range from GPS satellite to receiver} \\ c &= \text{speed of light in a vacuum} \\ dt_{RX} &= \text{receiver clock bias, in seconds} \\ dt^{SV} &= \text{SV clock bias, in seconds} \\ T &= \text{tropospheric errors} \\ \alpha_t STEC &= \text{ionospheric errors} \\ dp &= \text{SV ephemeris errors} \\ K_{P,R} &= \text{RX instrument errors} \\ K_P^S &= \text{SV instrument errors} \\ M_P &= \text{multipath} \\ \epsilon_P &= \text{noise} \end{aligned}$$

where the ionospheric errors are the product of the slant angle α_t and the slant total electron count $STEC$. If ephemeris, instrument, and multipath errors are ignored, then we get the simplified pseudorange equation

$$PR = \rho + c(dt_{RX} - dt^{SV}) + T + \alpha_t STEC$$

Solving for SV Position The second piece of data needed to solve for receiver position are the GPS satellite positions at the time they transmitted their pseudoranges. As mentioned previously, the pseudorange is the range between the receiver at t_{rx} and the Sv at transmittal time t_{tx}, but to make use of this measurement it is necessary to know the position of the SV at t_{tx}, and to do that requires knowledge of $\Delta t = t_{rx} - t_{tx}$. This "transit time" is determined to be the true range divided by the speed of light. In order to cover this transit time, it is best to start with an initial estimate using the pseudorange, then iterate to gain a better estimate of the true tranist time. Fortunately, the flight software compensates for the atmospheric errors (ionospheric and tropospheric effects) as well as the SV clock bias. Thus, the pseudorange measurements can be defined as

$$PR = \rho + c(dt_{RX}) + r\,,$$

where r represents random white noise.

Verification. One method to verify that the RINEX observation file is correct is to take the RINEX observation file, and its associated RINEX navigation file, and to process these through GPS software receiver code. A modified version of SoftGNSS (a Matlab GPS software package) was used to generate a trajectory for the Artemis ascent and reentry data, and checked to see if it seemed reasonable when compared to the recorded Artemis trajectory.

Filtering and Smoothing

As mentioned in the previous section, the BET framework, including the trajectory estimation, is to be handled by FreeFlyer. A black-box full covariance EKF architecture is used in estimating the navigation state, which includes the vehicle's position and velocity (in ICRF), as well as the GPS receivers' clock bias and clock drift, and a three-dimensional generic acceleration bias term (also in ICRF). The filter states are initialized off of the corresponding onboard state estimates at the start time of interest. The ICRF acceleration bias terms are initialized to zero and the EKF covariance initialization is selected such that the states are independent, and in the case of multi-dimensional states, homeostatic. The states are propagated using an Runge-Kutta 8(9) integrator, modeling gravitational effects of the Sun and Moon as point masses and an Earth gravity model of degree- and order-24. Non-gravitational forces are modeled using an external force file as described in the previous section. Covariance propagation in the EKF incorporates an acceleration noise covariance and a process noise covariance. It should be noted that since the FreeFlyer EKF handles accelerations in ICRF, this acceleration noise covariance term is not perfectly representative of the IMU measurement noise covariance; however, the values used in the BET generation are chosen such that the effect on the covariance growth is appropriate for a given phase of flight.

Once a forward filtered state and covariance solution is produced, the results are processed again in FreeFlyer using the black-box Rauch-Tung-Striebel (RTS) smoother. The output state history is the delivered BET profile.

Incorporation of External Data Sources

Many external observations were collected over the duration of the mission, one of the most informative being the doppler and range observations acquired by the DSN stations in Madrid, Spain; Canberra, Australia; and Goldstone, California. These observations were processed in a ground navigation filter in the Mission Control Center (MCC) to maintain a navigation solution on the ground that could be uplinked periodically over the course of the missions. These navigation solutions provided an updated mean and covariance to the vehicle at set points in the mission timeline; these ground state updates were to be processed in the BET filter as a "measurement" of the full vehicle state, with the intent of incorporating the raw measurement data into the BET as the data becomes available. Additionally, radar observations were taken during entry from the recovery ship.

Unfortunately, due to resource limitations and time constraints, these external data sources were not incorporated into the final BET. Rather, an adjacent effort was spun up to evaluate the ground navigation tools of Mission Control, resulting in an evaluation of the NASA Jet Propulsion Laboratory tool Monte [10]. This tool provided the capability to not only process DSN measurements, but also to estimate a range bias during each observation pass (i.e. every time span over which a specific DSN site was in communication and receiving observational data). Preliminary results indicate the Monte tool will provide the best possible trajectory estimation for the orbit phase of the flight. It is for this reason that the orbit phase is omitted from the scope of this work.

RESULTS

For the myriad of reasons alluded to in the preceding sections, the framework and the resulting BET is several steps shy of the desired finished product. Due to this fact, as well as associated export control concerns, a limited scope BET is presented here, namely the entry profile used to seed the best wind estimate and entry performance analysis. Though it does not explicitly process external data, the entry profile does provide a fairly complete sample of the full BET generation process, as it exhibits the flight data pre-processing steps for the on-board sensor data as well as how the translational and rotational states are handled within the framework. The following section will provide details on the data used in the entry profile, the initialization of the forward filter, and finally the resulting BET and how it compares to the on-board solution.

Accelerometer Data

It has been discussed at length the complications experienced in decommutating the flight data, in particular the high-rate 200 Hz OIMU data. An illustration of the data chatter issues present in the full-rate data can be seen in Figure (2) (though with the y-axis labels removed due to ITAR restrictions). This plot shows the accelerometer readings in all three axes over a duration of two seconds, represented in the IMU computational center frame. Note that the noise is very similar in appearance to quantization errors, as the "noise" on the signal is in discrete jumps. However, those jumps are different across all three channels, and the magnitude of the jumps themselves are a fraction of the actual quantization value. This is one example of the deficiencies present in the full-rate data, and while efforts and analyses were performed to discern the exact cause of these deficiencies, the BET effort necessarily had to progress.

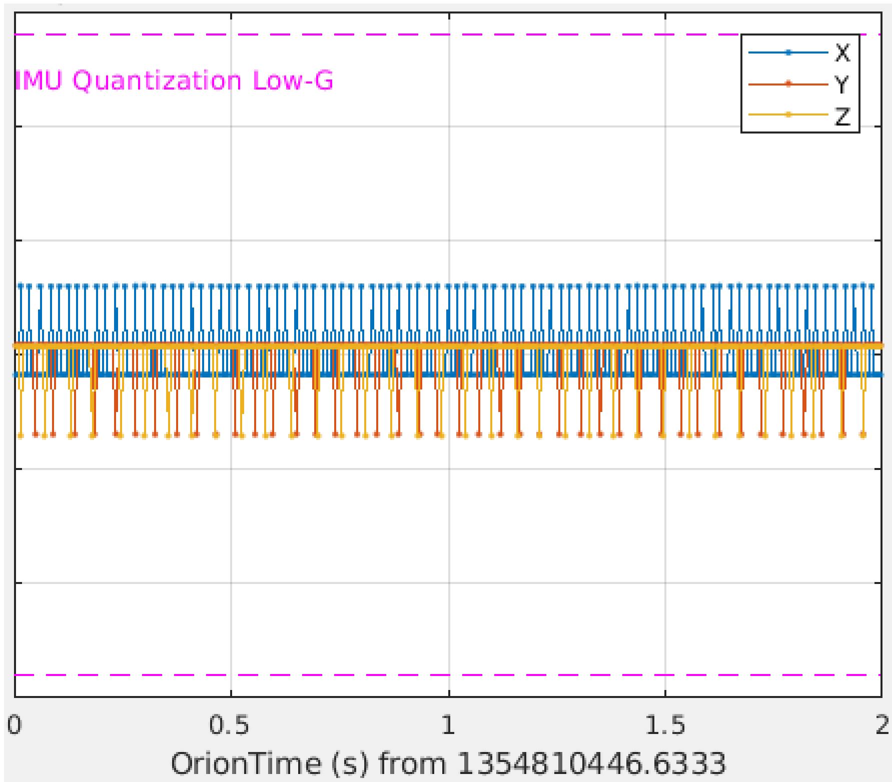

Figure 2. Full-rate 200 Hz accelerometer data plotted during quiescent flight, along with the quantization level for the OIMU when it is in low gravity mode.

Consequently, the 40 Hz OIMU data was used due to its superior quality (relative to the 200Hz data), as the issues present in the full-rate data are much less noticeable in the 40 Hz signals. A sample of the 40 Hz data can be observed in Figure (3) over both a 60 second and 10 second span. The 60 second view shows some banding that more similarly resembles the quantization effects that would be expected; however, zooming in to the 10 second view shows some "streaky" behavior that may or may not be related to the data decompression and decommutation. Regardless, as it was the best acceleration data source available at the time of generation, it was used to generate the external force file for the BET propagation.

GPS Data

As explained in the GPS RINEX File Reconstruction section, the quality and format of the GPS data necessitates an independent sanity check to verify that the data has been appropriately reconstructed. This enabled iterations to be performed on the RINEX reconstruction to ensure that the measurement data had the corrections and corruptions that the BET framework was expecting. For instance, through this verification it was discovered that the transit time necessarily must be included in the pseudorange data for the measurements to be processed correctly. It also enabled some amount of post-processing to occur, e.g. it was noted that the SV associated with PRN 26 was not healthy during the entry phase of the mission, and could subsequently be removed from the RINEX file. After several iterations, a suitable RINEX file was generated and a batch least squares solution generated independently from the BET framework. This estimate was compared against the

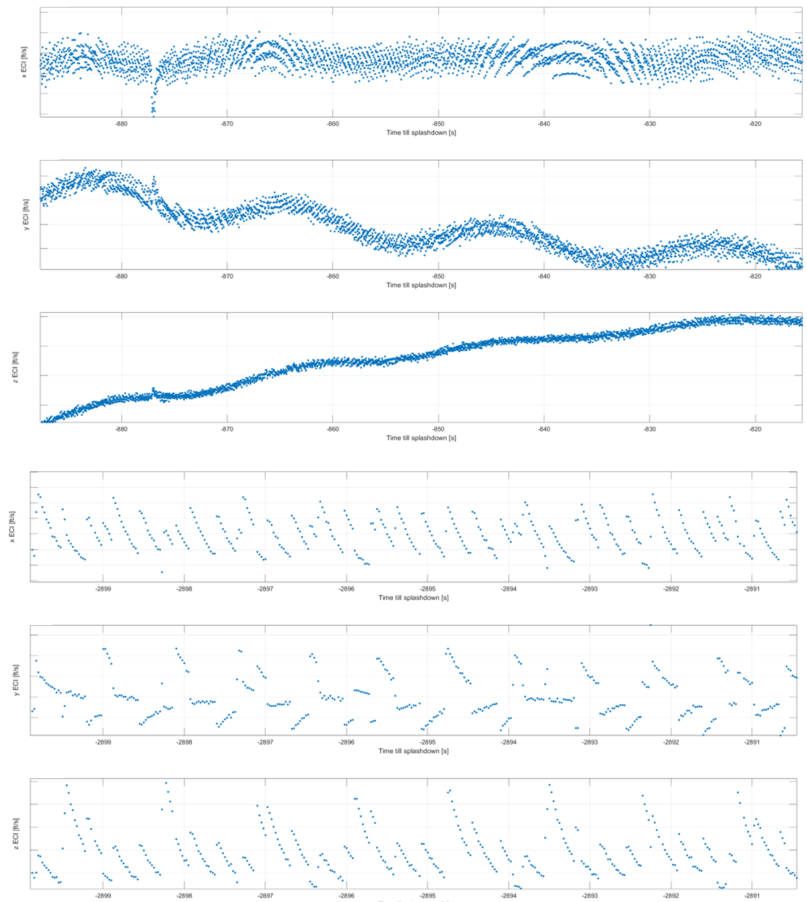

Figure 3. The resulting 40 Hz acceleration signal computed on-board from the 200 Hz IMU data. (Top) a 60 second span. (Bottom) zoomed in to a 10 second span.

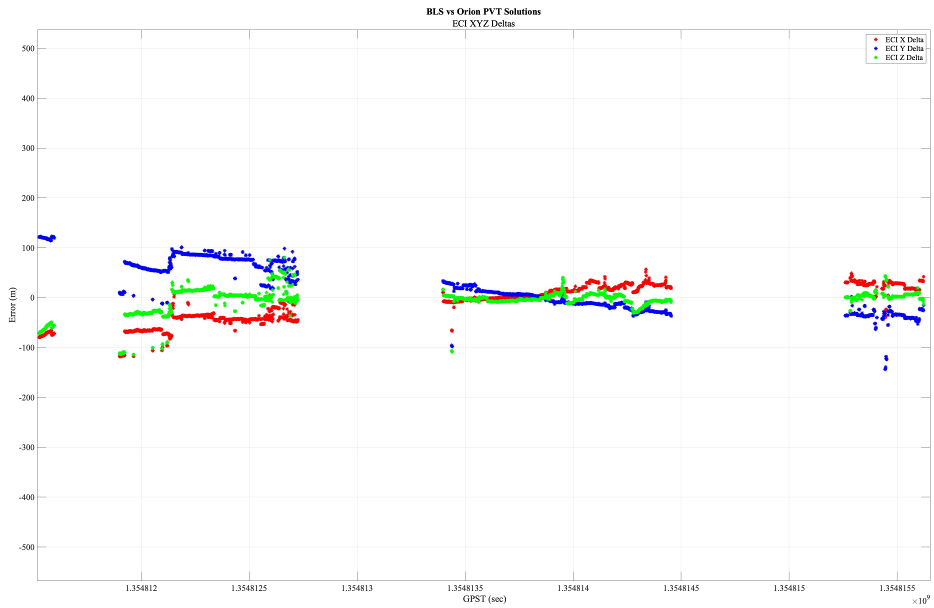

Figure 4. A batch least squares (BLS) generated estimate of the Orion entry profile compared against the GPSR PVT solution.

on-board GPSR position, velocity, time (PVT) solution, and the results can be seen in Figure (4).

The residuals in Figure (4) seem rather large in the first two bands of measurement data. However, as Orion approached entry, the GPSR that recorded this data had a favorable orientation and the GPS constellation was in a fortunate state such that reacquisition occurred at a much higher altitude than expected. The performance in the latter two bands of data are much closer to expectations, with some of the residuals likely due to the lack of a sequential estimate of the clock bias being available. Ideally, the two large gaps present would be filled by data extracted from the physical computer upon recovery of the vehicle; gaps are expected due to GPS blackout periods in the reentry profile, but a portion of these gaps are due to data loss during the mission.

BET Initialization

The BET was developed in phases as the data became available and as the need arose within the analysis community. Consequently, the entry profile was generated first. Of course, the beginning of the entry pofile does not benefit from the convenient initialization point of the launch pad; however, prior to entry a navigation solution was generated on the ground from the DSN data and up-linked to the vehicle to tighten up the on-board state in preparation for entry.

As a note on the attitude state, it was originally intended that some thought and consideration would go into the attitude profile during the ascent and entry phases of flight. The star trackers provide an excellent estimate of the attitude state on orbit, but nominally the BET would at least propagate the attitude state via the on-board gyroscope data when the star trackers become unavailable during entry. In light of the issues present in the data and the fact that the commercial off the shelf software employed would have required a significant overhaul to simultaneously estimate the attitude state in parallel with the position and velocity, the on-board attitude estimate history was used for the attitude profile. While not ideal, this attitude profile is initially informed by the star trackers prior to entry, maintains a marginal amount of attitude information upon GPS acquisition, and importantly was maintained using the full-rate gyroscope data within flight software, a luxury that was not available at the time of this effort.

BET Performance

The entry BET is generated using GPS and IMU data, processed and formatted for use in FreeFlyer as detailed in the preceding sections. PR data are provided to the EKF in four distinct sets. Figures (5) and (6) show the pre- and post-update residuals of the EKF over the entire entry BET. Both Figures (5) and (6) show a constrained y-axis that omits a handful of larger residuals that occur at the beginning of each measurement pass. These measurement residuals are omitted in the figures for the sake of visibility and show convergence towards zero over time in all cases. It should also be noted, that there are no measurements rejected in either the onboard filters or BET EKF due to residual editing. The residual editing threshold in the BET EKF is given as five times the measurement standard deviation. Due to the orientation of the GPSRs on the spacecraft, the first two sets of PR data (approximately [-4090, -4020] seconds and [-3700, -2900] seconds relative to splashdown), contain measurements from a single GPSR, while the last two (approximately [-2220, -1160] seconds and [-350, 0] seconds relative to splashdown) contain measurements from both GPSRs. Comparison of the residual trends between Figures (5) and (6) show the desired reduction in measurement residuals due to the Kalman filter update - suggesting the filter is accepting and processing measurements correctly.

Satisfactory performance of the BET forward-filtered, backward-smoothed pipeline is determined via comparison of the state solution to the onboard values. Results for the entry profile position and velocity ICRF state estimates are given in Figures (7) and (8), respectively. Data are presented as ICRF error relative to the onboard solution with the BET EKF uncertainty (given as $\pm$ three times the standard deviation). It should be noted that the onboard-relative error is not perfectly representative of the truth-relative error the EKF uncertainty characterizes; however, without a known true state, it is the closest available approximation for inspecting the BET filter behavior.

The position results in Figure (7) show significant difference with respect to the onboard solution during the first GPS measurement pass, starting at around -4080 seconds prior to splashdown. While the EKF is initialized using the onboard solution two minutes before GPS acquisition, the dynamics and measurement processing parameters of the BET EKF differ from those of the onboard solution, resulting in different convergence characteristics for the two filters. Since the corresponding GPS PR residual behavior is desirable, the short-lived discrepancy is deemed acceptable. The velocity difference results in Figure (8) during this time period show a similar, but less dramatic, error jump followed by a rapid convergence towards zero.

After convergence the onboard and EKF solutions remain in good agreement and within the BET EKF uncertainty through the next two sets of GPS measurements until the GPS blackout at approximately -1200 seconds before splashdown. During this portion of reentry, the onboard-relative error for the BET EKF grows rapidly, especially in the ICRF z-axis velocity and position. The vector magnitude error behavior (pink + in Figures (7) and (8)) shows the z-axis velocity is the dominant difference relative to the onboard solution. Large differences in both position and velocity estimates are presumed to be caused by several factors. The primary source of error is the aforementioned IMU data quality issue. The small and slow growing difference in position and velocity estimates during orbit/coast phases of flight suggests the IMU data are not corrupted to the point they should be deemed unusable; however, the lower-rate and lower-quality data recovered for entry (compared to what was available to the onboard filter) results in less than ideal capture of rapidly changing atmospheric forces and a subsequent lower quality state estimate. GPS re-acquisition post-blackout quickly brings these estimates back in line with the onboard solution through the end of the timeline. The only exception during the final minutes of the descent is a brief velocity difference increase shortly before splashdown.

CONCLUSIONS

The Artemis I mission was by and large a success, thoroughly exercising the vehicle and the processes and procedures executed on the ground to fly it. This test flight exposed some significant issues in the data pipeline process by the high-rate data from the vehicle are recovered on the ground to perform post-flight analyses. While several flight test objectives were able to be performed and closed out with the data that was telemetered during the mission, this paper attempts to capture the complications caused by these data recovery issues for prosperity and to emphasize the need to address them going forward. Fortunately, the

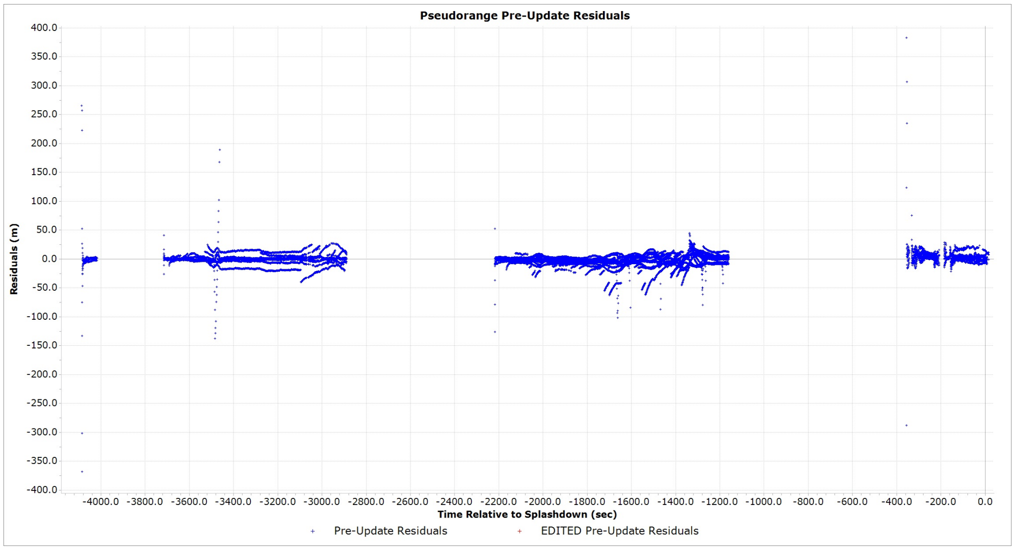

Figure 5. Entry BET GPS PR Pre-Update Residuals

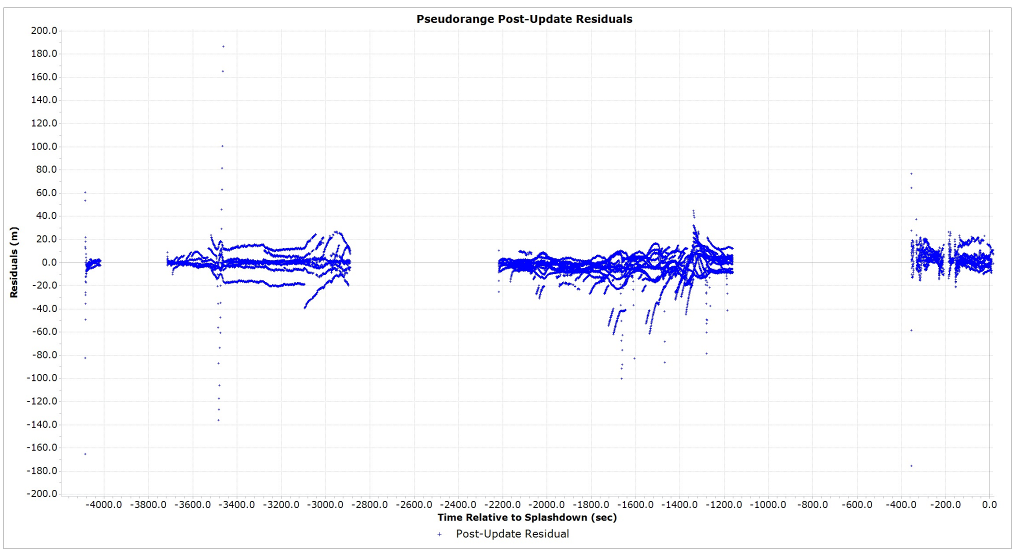

Figure 6. Entry BET GPS PR Post-Update Residuals

data was sufficient to still generate a position and velocity history that is largely independent of the on-board filter, providing another datum to which flight and tool performance can be measured against.

Perhaps even more importantly, identifying these issues has also spun up efforts to develop tools such that NASA will be better equipped to tackle them in the event they arise again in subsequent missions. Regardless, it is important that more resources be allocated in future missions to both the data architecture and recovery efforts as well as the best estimated trajectory development; many teams depend on a BET to perform their post-flight analysis, and until the data recovery process is solidified these issues will continue to plague future Artemis missions and critical analyses.

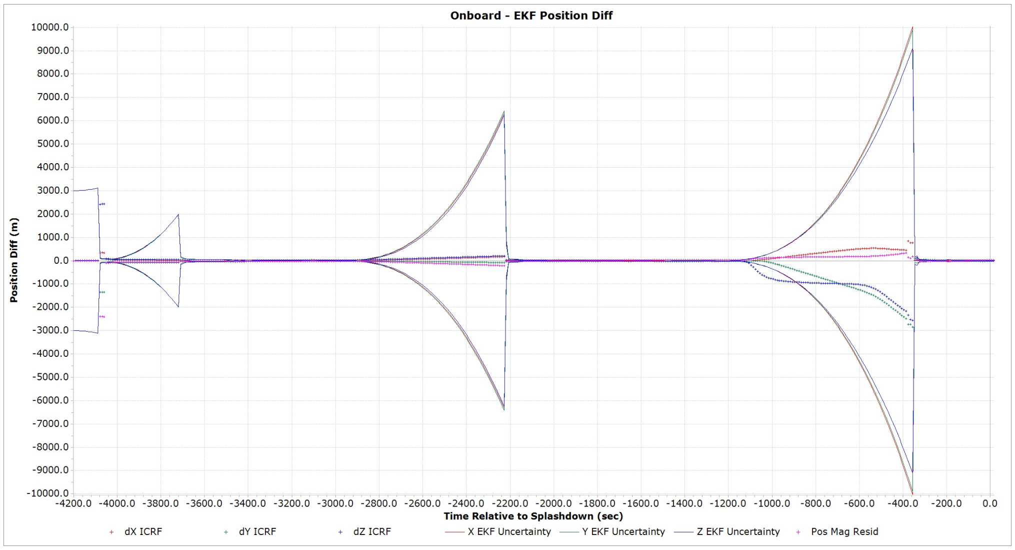

Figure 7. Entry BET ICRF position relative to the onboard solution, EKF uncertainty given as $\pm 3\sigma$

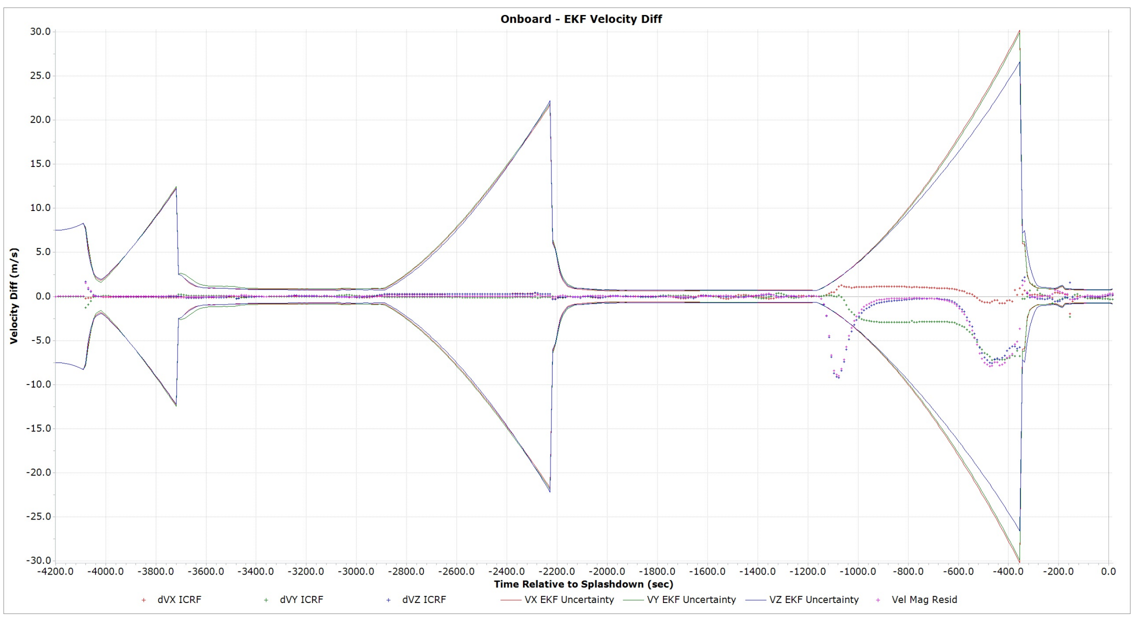

Figure 8. Entry BET ICRF velocity relative to the onboard solution, EKF uncertainty given as $\pm 3\sigma$

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