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ORION EXPLORATION FLIGHT TEST 1 (EFT-1) BEST ESTIMATED TRAJECTORY DEVELOPMENT

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The Orion Exploration Flight Test 1 (EFT-1) mission successfully flew on Dec 5, 2014 atop a Delta IV Heavy launch vehicle. The goal of Orions maiden flight was to stress the system by placing an uncrewed vehicle on a high-energy trajectory replicating conditions similar to those that would be experienced when returning from an asteroid or a lunar mission. The Orion navigation team combined all trajectory data from the mission into a Best Estimated Trajectory (BET) product. There were significant challenges in data reconstruction and many lessons were learned for future missions. The team used an estimation filter incorporating radar tracking, onboard sensors (Global Positioning System and Inertial Measurement Unit), and day-of-flight weather balloons to evaluate the true trajectory flown by Orion. Data was published for the entire Orion EFT-1 flight, plus objects jettisoned during entry such as the Forward Bay Cover. The BET customers include approximately 20 disciplines within Orion who will use the information for evaluating vehicle performance and influencing future design decisions.

INTRODUCTION

Following Orion's successful maiden flight in December 2014, the Orion navigation team combined all trajectory data from the mission into a Best Estimated Trajectory (BET) product as seen in Figure 1. This product is important for verifying the flight test objectives as well as validating preflight simulations and models. The data for the BET included radar tracking for ascent/entry/orbit, onboard sensors (Global Positioning System and Inertial Measurement Unit), and day-of-flight weather balloons. The customers for the BET product within the Orion program included GNC, Aerosciences, structures, thermal, orbital debris, and parachutes. The BET was also utilized by external customers including Exploration Systems Development and the FAA.During the buildup to flight in 2013-14, a number of student interns were instrumental in efforts to get the BET tools ready for flight. Unfortunately, there was not enough flight-like lab data to verify the tools and processes and substantial rework was required.

LIMITATIONS

The BET uses high rate IMU data to calculate inertial acceleration, attitude, angular rates, and angular accelerations. IMU to Center-of-Gravity transformations are done to preflight specifications and do not account for misalignment of the structural or aerodynamic frame (i.e., navigation is done on the IMU box). The BET also uses uses gyro and accelerometer reconstructions from

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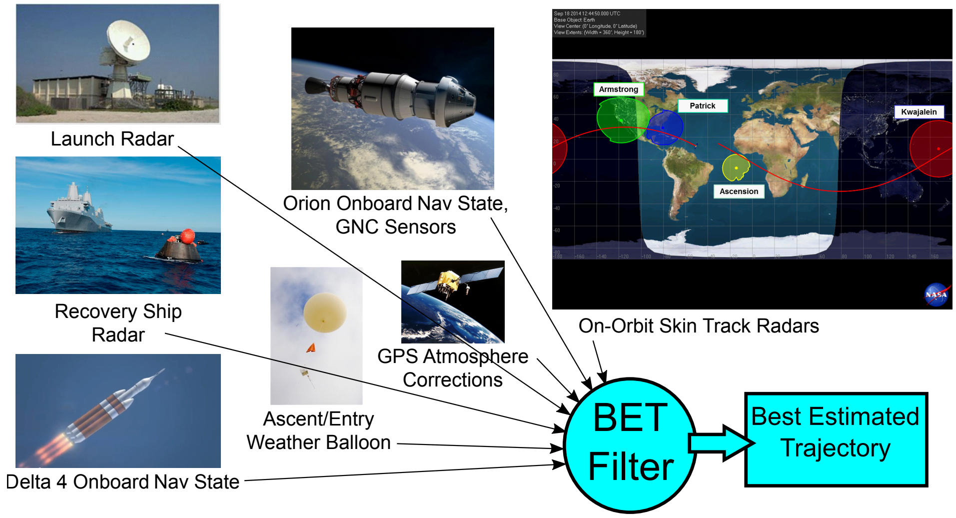

Figure 1. Best Estimated Trajectory Data Sources

L-30seconds to L+3seconds (the flight software recorder data was not available during this time frame). Atmospheric parameters were calculated using day-of-flight balloon data up to ∼24km for the entry phase and up to ∼33km for the ascent phase. Above these altitudes, Earth Global Reference Atmosphere Model (GRAM) 2010 V4.0 monthly mean[1,2] data was used for the atmospheric parameters, except for density and pressure values which were derived from onboard flush air data sensors. GRAM was still used for winds above 24km.

Coordinate Frames

Attitude information in the BET is derived from the IMU, and is therefore ultimately tied to the IMU case-frame coordinate system. The "OB" (Orion Body) frame is defined as simple transformations and rotations from the IMU, so any misalignment between the IMU and structural or aerodynamic (i.e., Outer Mold Line) frames will cause discrepancies in quantities related to those frames (e.g., Angle of Attack). Aerodynamic parameters during the hypersonic entry phase are derived in a BET addendum from FADS sensors and will not strictly agree with the inertial attitude at those times. The standard transformations used for IMU-derived data followed Orion spacecraft conventions.[3–5]

ESTIMATION FILTER

The primary estimation filter used for the BET was the Extended Kalman Filter implementation in FreeFlyer (Commercial-Off-The-Shelf software from a.i. Solutions, inc.). The setup of the estimation filter is as follows. Note the filter was purposely tuned "tightly", meaning measurement noises were generally smaller than would be used for a robust real-time filter. Some of the setup and tuning values are given here to provide context and a rough idea of the filter setup for the processing statistics plots later in the paper. Polar Motion and UT1 Correction were applied, with Earth Nutation/Precession updated every 1800 seconds. Ionospheric refraction of GPS and radar signals was modeled using IRI2007 from 80-1500km, with 25km integration step size. A Runge-Kutta 8(9) integrator was used with a 1e-9 relative error tolerance and maximum step size of 0.025 seconds. Earth gravity was modeled with an 8x8 degree/order EGM96, while Sun & Moon gravity were modeled as a point mass. The filter state consisted of Position, Velocity, GPS Clock Bias, and GPS Clock Drift. The GPS pseudorange measurement noise was modeled as 10 meters for single frequency L1 data (this turns out as one of the limiting factors in the accuracy of the BET). Ascent radar data was provided as a solved position and velocity from the Eastern Range processing center, and the measurement noises used for processing were 46 meters and 0.6 m/s respectively. The radar data during orbit and the ship entry radar was provided as range/azimuth/elevation measurements. The processing noise value used for range was 20 meters and for angles 0.1 deg based on heritage processing of this data for the space shuttle. The GPS constellation was modeled using International GNSS Service Rapid Ephemeris for GPS week 1821 (sufficient accuracy for processing single-frequency data). The elevation measurements from NASA Armstrong radar were not processed as they were inadvertently double corrected for refraction, but the impact was minimal since GPS coverage was good during that portion of the flight. The Kalman filter was run with a position process noise of $10^{-6}m^2$ and velocity process noise of $10^{-5}m^2/s^2$. The GPS Clock Bias and Drift process noise values were $10^{-5}m^2$ and $10^{-5}m^2$ respectively.

PROCESSING FLOW

Figure 2 shows the processing flow for the BET. The "MATLAB Pre-Processing" block is further expanded in Figure 3.

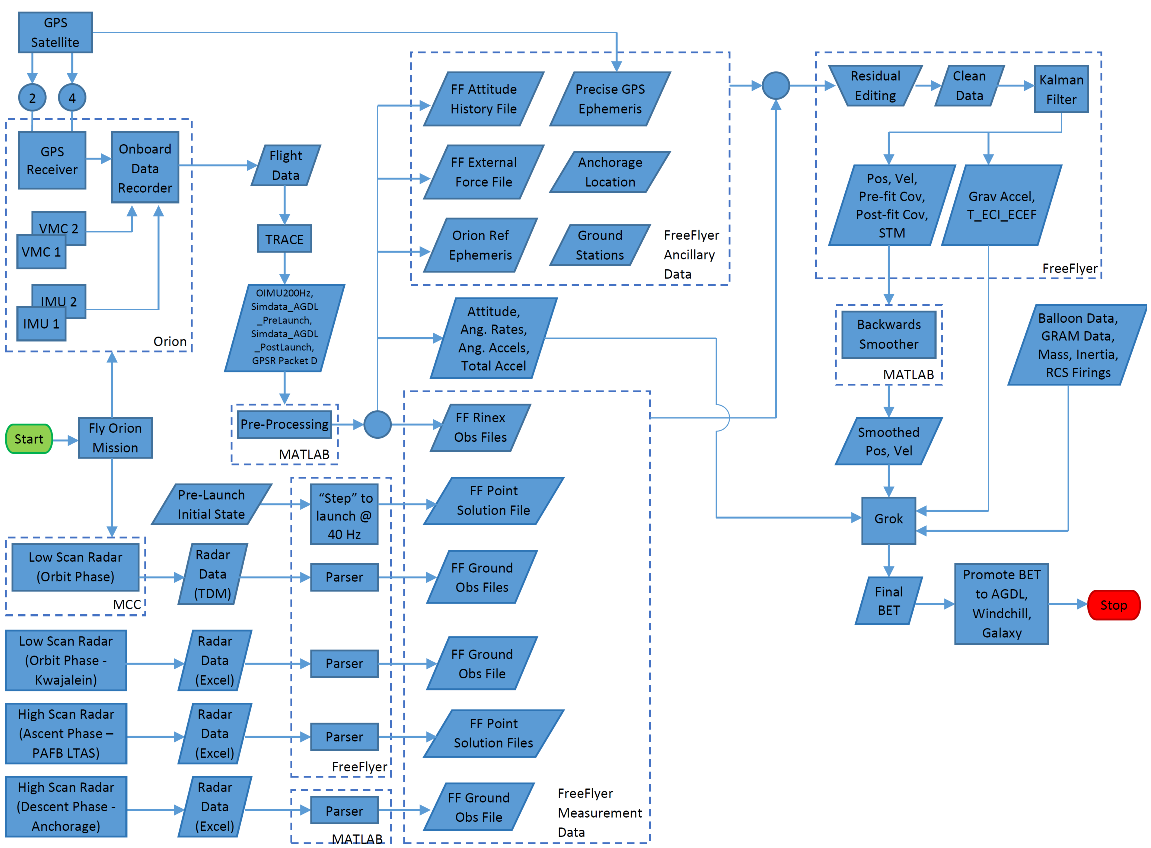

Figure 2. Best Estimated Trajectory Processing Flowchart

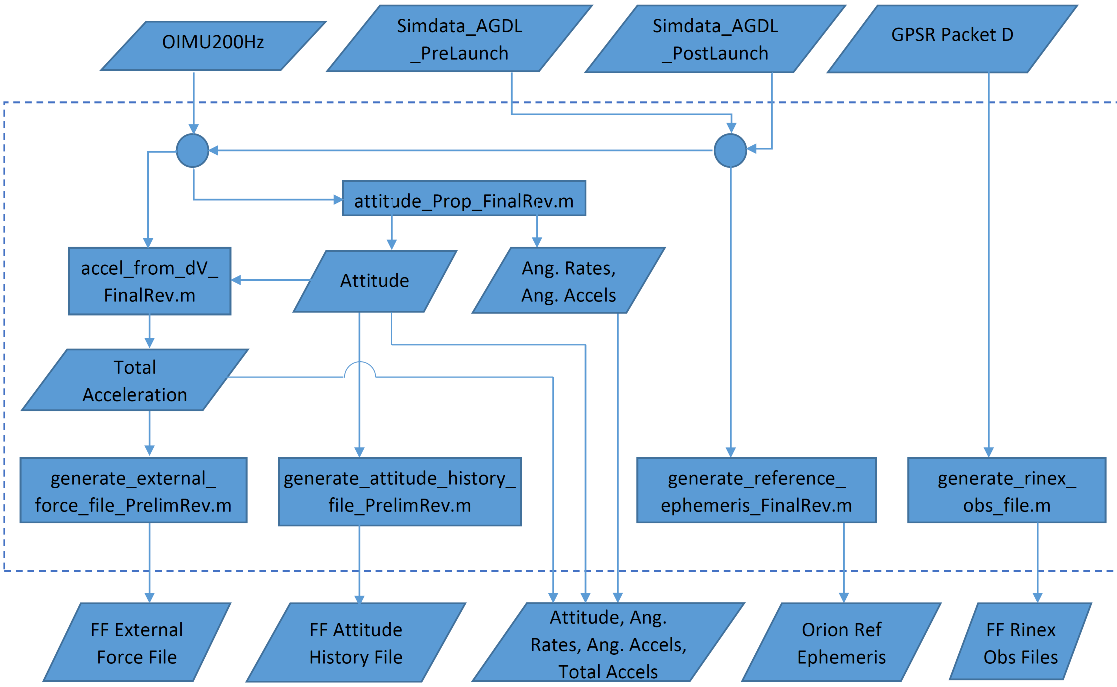

Figure 3. Matlab Pre-Processing Flowchart

Code Descriptions

The following is a list routines used in the BET process and special notes.

mf3_EFT1_ABSSUPP_PostProcess_PrelimRev This routine is used to pull the Minor Frame 3 ABSSUPP data for processing. The rest of the ABSSUPP data was corrupted. The prelaunch ABSSUPP position and velocity were inaccurate because of an incorrect software database load. For the Final BET, the prelaunch position and velocity were anchored to the correct Earth-fixed pad location.

attitude_prop_FinalRev An unexplained one second bias was found and corrected in the prelaunch telemetry timetags. The prelaunch gyroscope bias, scale factor, and non-orthogonality values were taken from later in the mission when the onboard estimates had converged (index 14200). The prelaunch and ascent attitude was backward propagated from an anchor point after main engine cutoff and GPS acquisition and convergence (index 720). The raw gyro delta-theta measurements were noisy (as expected), but the noise was generally concentrated in the higher frequencies. For this reason, derived angular rate and angular acceleration data was smoothed with a Butterworth maximally flat magnitude low-pass filter to preserve the responses at and below the 40Hz processing rate. This was accomplished in Matlab using:

$$[b, a] = \text{butter}\,(6, 1.5 * 2 * pi/200/pi) \tag{1}$$

The data for the Orion EFT-1 Final BET was derived from IMU1. The data from IMU2 was cross-checked for consistency but not used in the final product.

accel_from_dv_FinalRev Orion uses a strapdown IMU, so the inertial attitude of the vehicle must be known to convert the delta-velocity measurements taken in the IMU case frame into accelerations in the inertial frame. The attitude profile derived in *attitude_prop_FinalRev* is used for this purpose. As with the gyro compensation, the prelaunch accelerometer bias, scale factor, and misalignments were taken from later in the mission when the onboard estimates had converged ($\sim$1032 seconds MET). Again, the Butterworth filter was applied to the derived acceleration data to filter the expected high-frequency noise. The data for the Orion EFT-1 Final BET was derived from IMU1. The data from IMU2 was cross-checked for consistency but not used in the final product.

generate_external_force_file_PrelimRev This routine takes the true total acceleration from *accel_from_dv_FinalRev* and generates a formatted External Force file for use in FreeFlyer.

generate_attitude_history_file_PrelimRev This routine takes the true inertial attitude from *attitude_prop_FinalRev* and generates a formatted Attitude History File for use in FreeFlyer.

generate_reference_ephemeris_FinalRev This routine takes the inertial position and velocity from *mf3_EFT1_ABSSUPP_PostProcess_PrelimRev* and generates a formatted Reference Ephemeris for use in FreeFlyer.

Orion_BET - FinalAsRun_13Mar2015.MissionPlan The FreeFlyer mission plan "Orion_BET - FinalAsRun_13Mar2015.MissionPlan" takes in all of the measurement data and ancillary data per the BET Processing Flowchart and runs an extended Kalman filter to generate an unsmoothed position, velocity, time history of the EFT-1 spacecraft. The mission plan first provides the user with inputs that govern file names and file paths, flags for turning on tracking data editors, and flags for displaying plots. Next, the mission plan configures the Orion spacecraft object that is associated with the Kalman filter, as well as the ground station objects associated with the RADAR measurement data. Included with the ground station objects is a roaming ground station to represent the USS Anchorage. Following configuration, the mission plan shows any tracking data editors selected by the user. These editors provide the user with an opportunity to manually remove spurious measurements or otherwise suspect data points. The resulting clean data is then fed to the Kalman filter for processing. The final step before Kalman filtering is to provide external force data to the Orion spacecraft (i.e. sensed IMU accelerations) for propagations periods between Kalman filter measurement updates.

The Kalman filter section of the mission plan consists of a large While loop that loops over each line in the external force file. The Kalman filter is stepped to the next measurement epoch or the next IMU acceleration epoch, whichever comes first. If the next epoch is a measurement epoch, the Kalman filter steps to that epoch, loops through each measurement at that epoch, and incorporates the measurement into the filter. Any measurement residual-related plots are also updated with each measurement update. Finally, position, velocity, pre-fit covariance, post-fit covariance, and state transition matrix data are saved off at that epoch for use in the backwards smoother in MATLAB once the mission plan has completed. If the next epoch is an IMU acceleration epoch, the Kalman filter steps to that epoch, incorporates the new IMU accelerations into the Orion spacecraft force model, and gets the next IMU acceleration epoch and acceleration data. The final step in each pass through the While loop is to update the non-measurement residual plots (altitude, position covariance, velocity covariance). The mission plan completes once the Kalman filter section has looped through each line in the external force file.

read_smoother_inputs This routine reads the data output by FreeFlyer and converts to Matlab Timeseries objects. The data output by FreeFlyer consists of Pre & Post-Update Position, Velocity, Covariance Matrix, State Transition Matrix, ICRF/ITRF rotation, and Gravitational Acceleration.

backward_smoother Runs the Rauch, Tung, Striebel backward smoother detailed in subsequent section.

generate_GROK_inputs_FinalRev_Mar12 Generates the formatted inputs needed for the GROK software to process and generate inertial and aerodynamic parameters for the Final BET. These include the inertial accelerations from *accel_from_dv_FinalRev*, the attitude/ang-rates/ang-accel from *attitude_prop_FinalRev*, and inertial position/velocity from the *backward_smoother*.

Backward Smoother

A Rauch, Tung, and Striebel backward filter/smoother[6] was implemented on the position and velocity states output by FreeFlyer to take advantage of both past and future observation data and minimize discontinuities. The processing algorithm is given in Table 1.

Table 1. Rauch, Tung, and Striebel Backward Filter/Smoother

Model and Observation	
Model and Observation	$\mathbf{x}_k = \mathbf{A}_{k-1}\mathbf{x}_{k-1} + \mathbf{B}_{k-1}\mathbf{u}_{k-1} + \mathbf{w}_{k-1}$ $\mathbf{z}_k = \mathbf{H}_k\mathbf{x}_k + \mathbf{v}_k$
Forward Filter	
Initialization	$\mathbf{x}_{f0}^+ = \mu_0$ with error covariance $\mathbf{P}_{f0}^+$
Model Forecast Step/Predictor	$\mathbf{x}_{fk}^- = \mathbf{A}_{k-1}\mathbf{x}_{fk-1}^+ + \mathbf{B}_{k-1}\mathbf{u}_{k-1}$ $\mathbf{P}_{fk} = \mathbf{A}_{k-1}\mathbf{P}_{fk-1}^+\mathbf{A}_{k-1}^T + \mathbf{Q}_{k-1}$
Data Assimilation Step/Corrector	$\mathbf{x}_{fk}^+ = \mathbf{x}_{fk}^- + \mathbf{K}_{fk}\left(\mathbf{z}_k - \mathbf{H}_k\mathbf{x}_{fk}^-\right)$ $\mathbf{K}_{fk} = \mathbf{P}_{fk}^-\mathbf{H}_k^T\left(\mathbf{H}_k\mathbf{P}_{fk}^-\mathbf{H}_k^T + \mathbf{R}_k\right)^{-1}$ $\mathbf{P}_{fk}^+ = \left(\mathbf{I} - \mathbf{K}_{fk}\mathbf{H}_k\right)\mathbf{P}_{fk}^-$
Smoother	
Initialization	$\mathbf{x}_N^s = \mathbf{x}_{fk}^+$ $\mathbf{P}_N^s = \mathbf{P}_{fk}^+$
Update	$\mathbf{K}_k^s = \mathbf{P}_{fk}^+\mathbf{A}_k^T\left(\mathbf{P}_{fk+1}^-\right)^{-1}$ $\mathbf{P}_k^s = \mathbf{P}_{fk}^+ - \mathbf{K}_k^s\left(\mathbf{P}_{fk+1}^- - \mathbf{P}_{k+1}^s\right)\left(\mathbf{K}_k^s\right)^T$ $\mathbf{x}_k^s = \mathbf{x}_{fk}^+ + \mathbf{K}_k^s\left(\mathbf{x}_{k+1}^s - \mathbf{x}_{fk+1}^-\right)$

PROCESSING STATISTICS

Filter Residuals

The estimation filter residuals are shown in Figures 4 through 8. The ascent radar data was provided in terms of a processed position/velocity solution from the Eastern Range. The position residuals shown in Figure 4 are generally bounded within 200 meters. A spike is seen when the filter begins processing GPS measurements around 7 minutes MET, most notably in the inertial Y direction which roughly corresponds to the vehicle downtrack direction. The ascent radar velocity residuals are generally bounded within 1 m/s. Again, a spike is seen when the filter begins processing GPS measurements around 7 minutes MET.

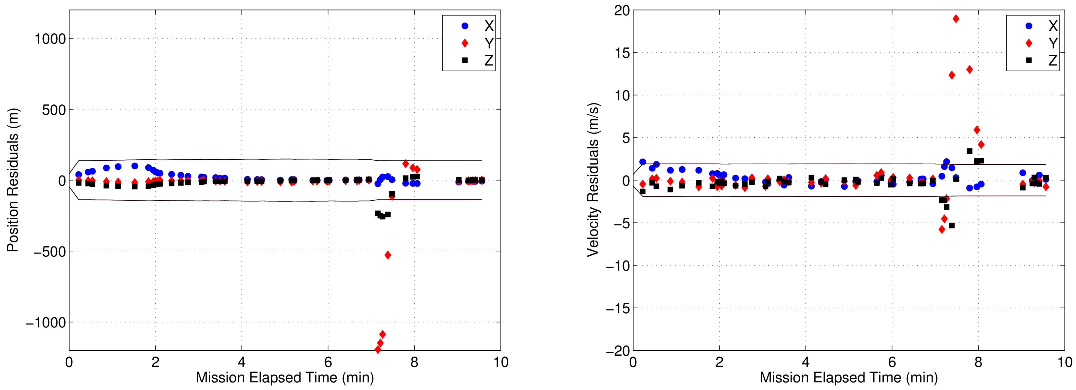

Figure 4. Ascent Radar Position & Velocity Measurement Residual and Innovation Covariance

The on-orbit radar range residuals in Figure 5 show good agreement with the BET. This data was in the form of Range, Azimuth, and Elevation measurements. The early pass from Ascension Island around MET 20min shows range residuals bounded within +/- 50 meters, as are the subsequent passes from NASA Armstrong and Patrick AFB around MET 100min. The second pass from Ascension around MET 140min is a long range pass as the vehicle is outbound on the high ellipse, so a range bias of around 70 meters is noted. The on-orbit angular measurement residuals were very well behaved and showed excellent agreement with the Final BET trajectory. The residuals were generally within 0.1 degrees in both azimuth and elevation. Note the elevation measurements were not used from Armstrong because of errors from a suspect atmospheric refraction correction.

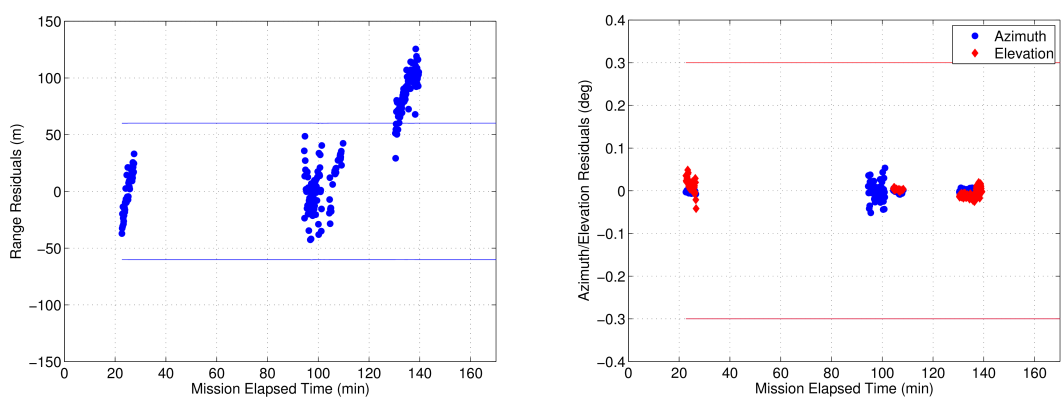

Figure 5. Orbit Radar Az/El/Range Measurement Residual and Innovation Covariance

The GPS pseudorange residuals were also well behaved through the flight, with some expected spikes manually edited due to atmospheric distortion for satellites at low tracking elevation. GPS pseudorange residuals are generally bounded within 10 meters during orbit coast as shown in Figure 6.

GPS pseudorange residuals during ascent and entry shown in Figure 7 were also well behaved,

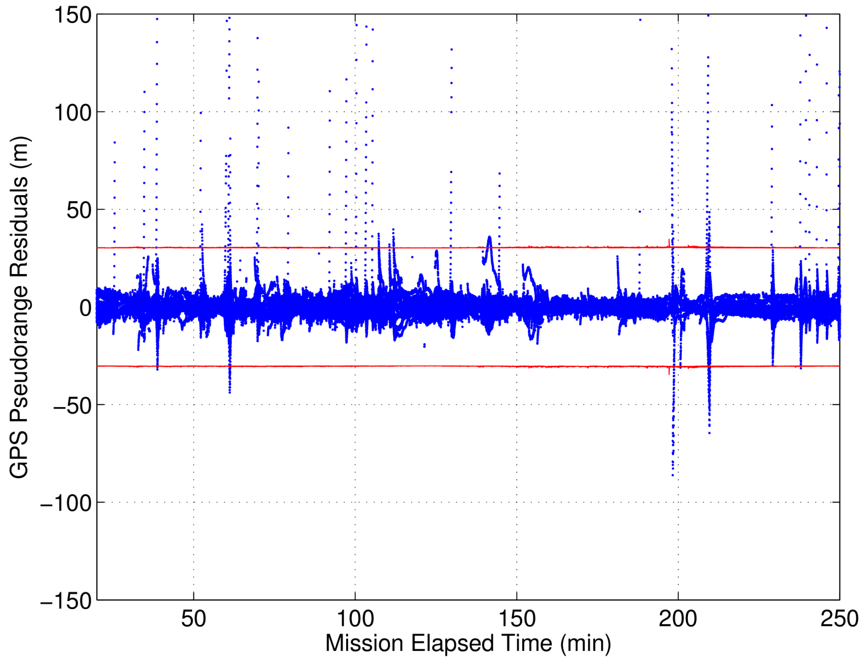

Figure 6. On-Orbit GPS Pseudorange Measurement Residual and Innovation Covariance

converging within a few seconds of reacquisition from plasma blackout and high angular acceleration cutout periods. The GPS pseudorange residuals during ascent showed reasonable convergence within 60 seconds of acquisition, and generally were bounded within 20 meters.

Entry Radar Range measurement residuals in Figure 8 showed good agreement with the Final BET. Early radar hits at long range had about a 600 meter bias, while close-in tracking was generally unbiased (or slightly negative) with a noise signature of +/- 300 meters. Entry Radar angle measurement residuals showed good agreement with the Final BET. Azimuth and Elevation were generally bounded within +/- 1.5 degrees.

Filter Covariance

The filter covariance is the internal representation of uncertainty in the estimation process and approximates the true error in the resulting trajectory. Notably, a filter of this type is tuned purposefully "tight", so the resulting covariance plots are likely to slightly under-represent the true error. The backward smoother reduces this uncertainty somewhat by taking advantage of future information content in estimating the current state. The position and velocity covariance plots are shown in Figures 9 through 11.

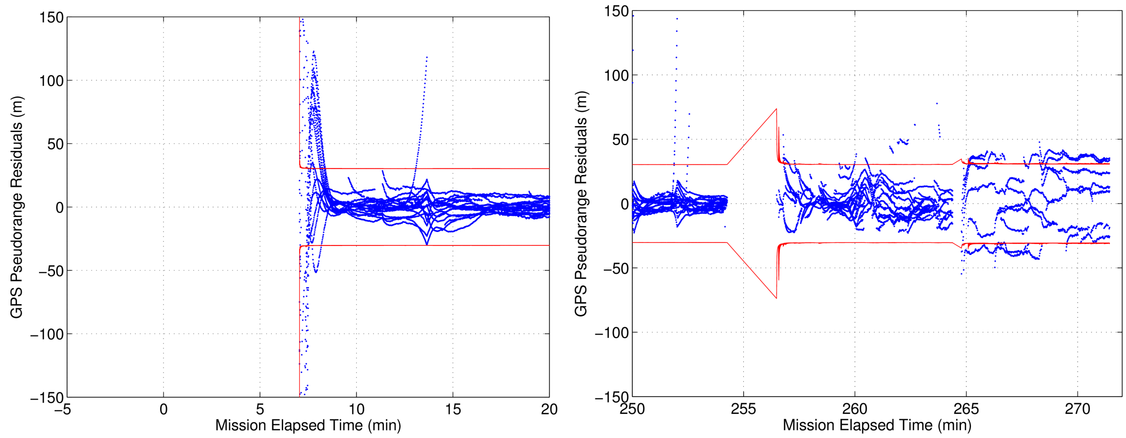

Figure 7. Ascent/Entry GPS Pseudorange Measurement Residual and Innovation Covariance

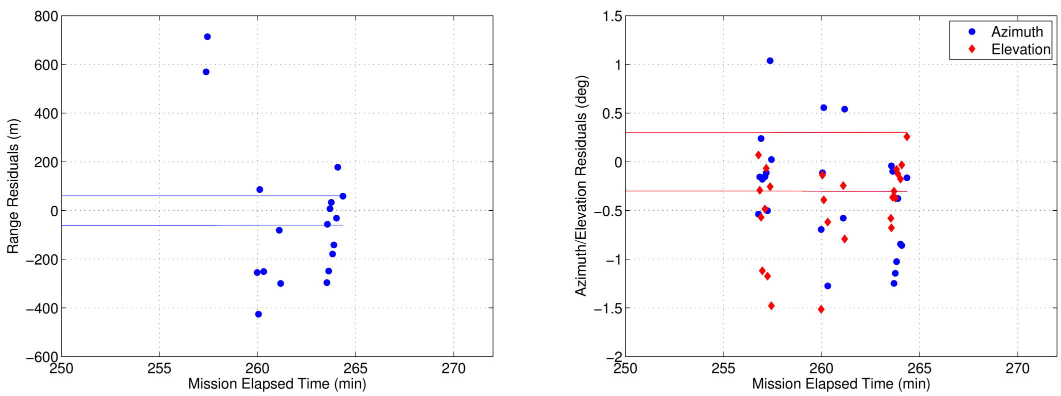

Figure 8. Entry Radar Range/Az/El Measurement Residual and Innovation Covariance

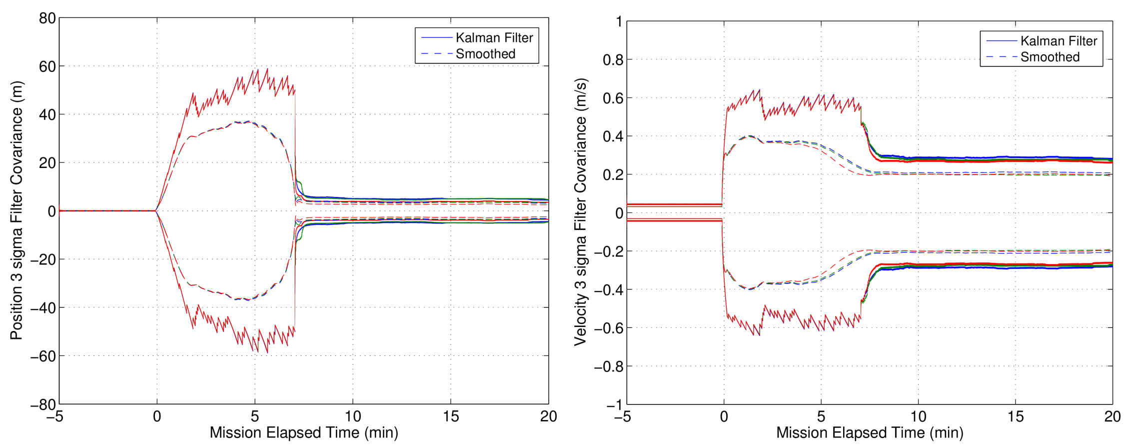

Figure 9. EKF and Smoothed Position Covariance - Ascent

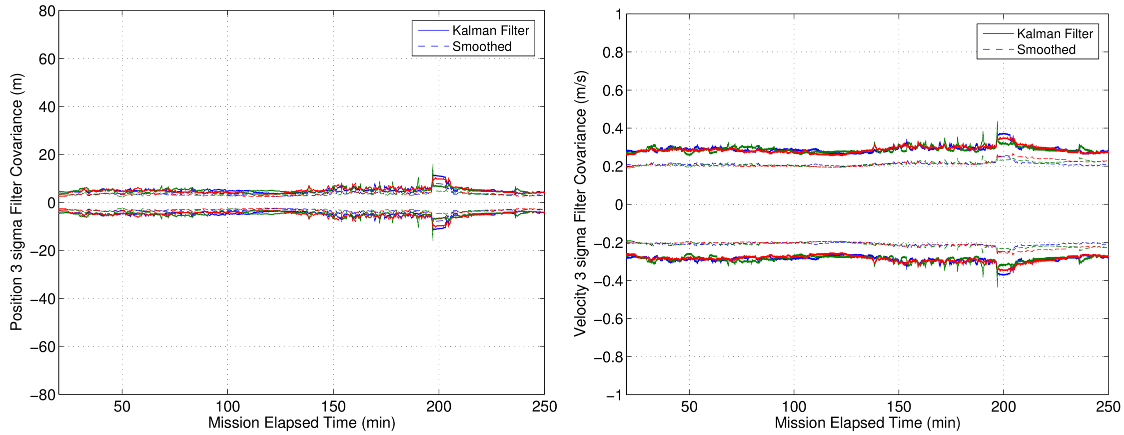

Figure 10. EKF and Smoothed Position Covariance - Orbit

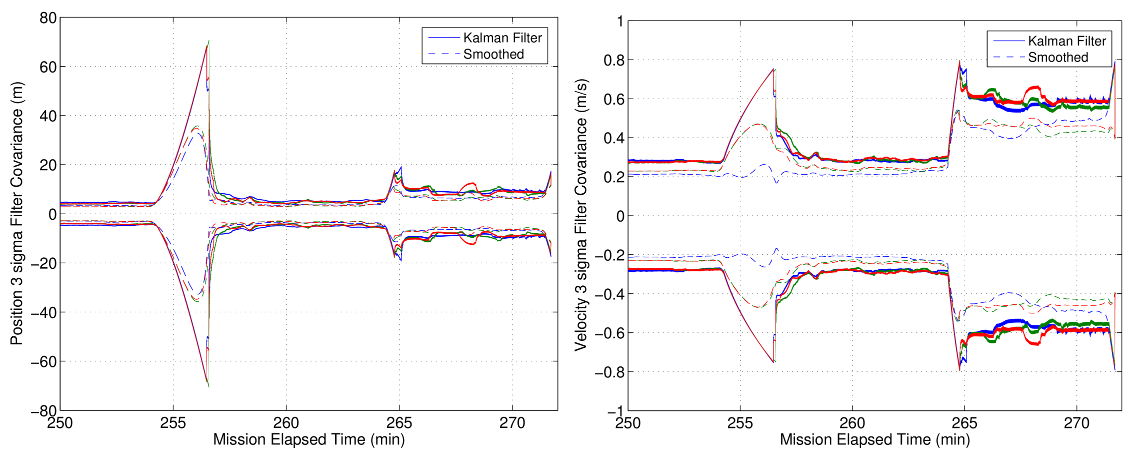

Figure 11. EKF and Smoothed Position Covariance - Entry

JETTISONED OBJECTS

The air-search radar on the recovery ship tracked the crew module (CM) and forward bay cover (FBC) during descent and landing. There were four other potential contacts which have not been identified to date, but are included for completeness. The best theories point to various covers and insulation blankets that are jettisoned as part of the drogue and main parachute deployment sequence. Radar returns were evaluated based on relative strength of return and dynamic consistency. Figure 12 and 13 shows the altitude profile of these objects.

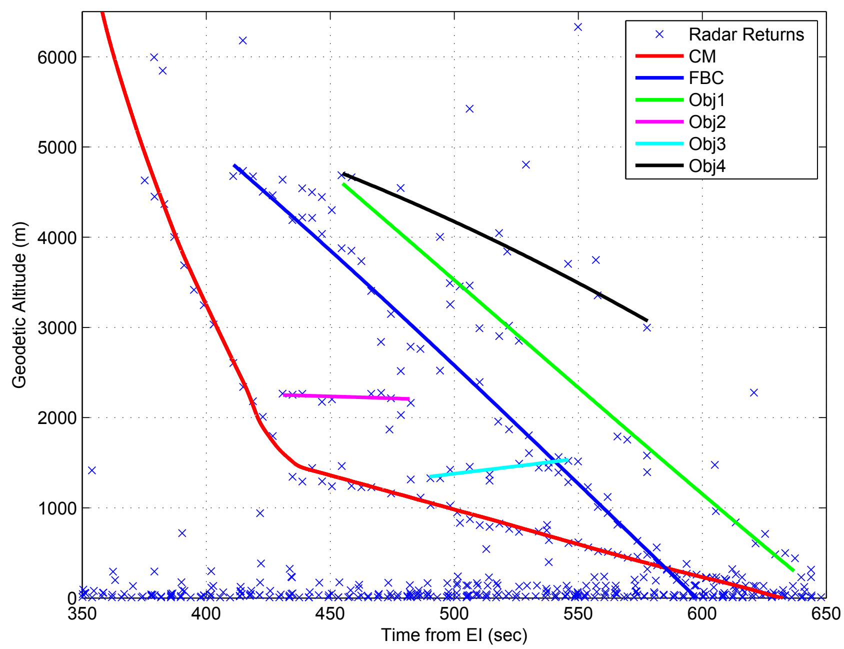

Figure 12. Reconstructed Altitude Profile Based on Entry Radar Tracking

PROCESSING CHALLENGES

There were a number of challenges encountered with extracting, time-synchronizing, and processing the data. Data corruption in the flight recorder was experienced, and while the clean data was eventually recovered it took much longer than expected. Because of these problems, the team had to rework the BET tools and processes significantly. Had telemetry experts been available to assist postflight, this rework would have gone much smoother. One particularly challenging piece was the timetag on the GPS psuedorange measurements. Per specification, the timetags were adjusted in the receiver by the amount of the kinematic clock bias solution to approximate proper GPS time. The initial processing setup in the BET filter included a pseudorange bias term which masked this effect and gave a "close" but slightly erroneous solution. When this term was removed from the BET filter, the entire clock bias was then properly estimated and the solution converged.

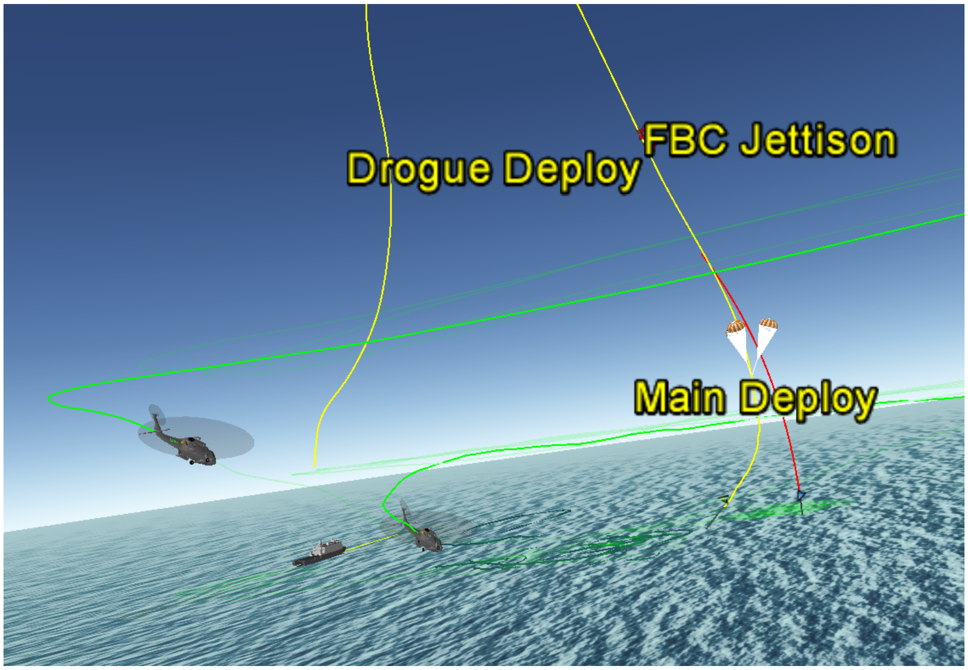

Figure 13. EFT-1 Entry and Recovery

LESSONS LEARNED

Some lessons were learned to pass along to future Orion flights and other programs. Having telemetry data extracted during a preflight lab run would have given early indication of trouble. Where possible, keep the data intact in the flight recorder rather than trying to reconstruct on the back end. If complex data compression is required, telemetry experts should provide standardized extraction software rather than downstream users such as GNC (given the multitude of subtleties in telemetry extraction). Having telemetry experts available immediately post-flight to help with data extraction would have saved hundreds of hours of wasted work.

ACKNOWLEDGMENTS

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